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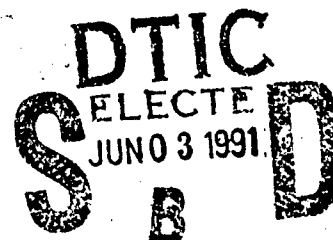
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Traffic Alert and Collision Avoidance System (TCAS)— Cockpit Display of Traffic Information (CDTI) Investigation

Phase I—Feasibility Study

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16. Abstract

The possibility of the TCAS traffic sensor and display being used for meaningful CDTI applications has resulted in the Federal Aviation Administration initiating a project to establish the technical and operational requirements to realize this potential. This report is the summary of Phase I of this project. Phase I has been organized to define specific CDTI applications for the terminal area, to determine what has already been learned about CDTI technology relevant to these applications, and to define the engineering required to supply the remaining TCAS-CDTI technology for capacity benefit realization. The CDTI applications examined have been limited to those appropriate to the final approach and departure phases of flight.

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FOREWORD

With the advent of the TCAS II airborne collision avoidance system, an airborne display of surrounding aircraft traffic is about to become generally available in the cockpit. It has been proposed that this cockpit display of traffic information (CDTI) provides the mechanism whereby the flight crew can assist the controller in tightening the spacing tolerances that are maintained between adjacent aircraft for many phases of flight. This possibility creates the potential whereby significant gains may be obtained with respect to increased airspace capacity and reduced flight delay.

The possibility of the TCAS traffic sensor and display being used for meaningful CDTI applications has resulted in the Federal Aviation Administration initiating a project to establish the technical and operational requirements to realize this potential. This report is the summary of Phase I of this project. Phase I has been organized to define specific CDTI applications for the terminal area, to determine what has already been learned about CDTI technology relevant to these applications, and to define the engineering required to supply the remaining TCAS-CDTI technology for capacity benefit realization. The CDTI applications examined have been limited to those appropriate to the final approach and departure phases of flight.

The TCAS-CDTI project has been managed by Malcolm Burgess of the FAA Engineering Field Office (ACD-20) at NASA Langley Research Center in cooperation with the FAA TCAS Program Office. The TCAS-CDTI Project Engineer has been Dean Davis of Diversified International Sciences Corporation (DISC).

The Phase I Project Operations Team has been responsible for defining CDTI applications in the terminal area and for suggesting needed technical investigation regarding requirements for flight safety, system certification, flight standards, and air traffic procedures. Members of the Project Operations Team include: Ward Baker of ALPA, Bill Cotton of United Airlines, Frank Cirino of American Airlines, Richard Danz of FAA Air Traffic, Mike Frank of United Airlines, Amy Kauffman of NATCA, R. J. (Pepe) Lefevre of APA, Frank Rock of FAA Certification, Daniel Schillaci of ATA, and Duane (Spyder) Thomas of FAA Flight Standards. Mike Frank has been Operations Team Leader.

The Project Technical Team has been responsible for (a) examining the applications from a requirements point of view, (b) determining what previous and on-going TCAS and CDTI research has been done that is related to this current effort, (c) determining to what extent the current TCAS II design is adequate to support the applications, (d) specifying need for further technical analysis and testing to realize the benefits of the CDTI applications, and (e) making recommendations for continuing the engineering development into a second phase of effort. Members of the Project Technical Team include: Sherry Chappell of NASA Ames Reseach Center, Dean Davis of DISC, Tsuyoshi Goka of T Goka Avionics, Walter Hollister of MIT Lincoln Laboratory, Carl Jezierski of FAA Technical Center, David Lubkowski of Mitre Corporation, John Sorensen of Seagull Technology Inc., and David Williams of NASA Langley Research Center. Each member has made contributions to the content of this report. John Sorensen has been Technical Team Leader and editor of the viewgraph presentations.

This is the final Phase I report prepared by the Technical Team. John Sorensen, Walter Hollister, Malcolm Burgess, and Dean Davis have served as co-editors. The Phase I effort was conducted over the period of February through June 1990.

CONTENTS

I. PROJECT OVERVIEW

Background

The concept of a Cockpit Display of Traffic Information (CDTI) has been suggested and studied since sometime in the 1940's. The TELERAN system, developed by RCA and tested in a Link trainer and a C-47 in the late 1940's, was based upon television transmission of ground radar information and map overlays to the aircraft. In 1947, the MIT Radiation Laboratory proposed two restricted visibility condition traffic display concepts: an airborne radar capability to derive traffic, terrain, and weather information and presentation of ground radar detected information on a cockpit PPI display. In 1948, the Radio Technical Commission for Aeronautics (RTCA) recommended that future domestic air traffic control be based on both ground and airborne pictorial situation displays.

Airborne station-keeping equipment has been employed successfully by the military services for many years to maintain safe air-to air separation in formation flying. In 1963, the Air Force flight tested the RATAC system in which ground radar information was transmitted via a TACAN data link to an airborne television to display nearby aircraft. Alphanumeric text was also transmitted and displayed to demonstrate the feasibility of providing flight clearances, weather advisories, and other pertinent information to the pilot. In 1965, a televised picture of the FAA's Boston TRACON display was used to test navigation and conflict detection concepts for general aviation. In 1974, MIT Lincoln Laboratory developed a digitized version of CDTI. The target data base was supplied by an Air Force 407L radar system via the SEEK BUS data link; this concept was later reconfigured for the USAF Airborne Warning and Control System (AWACS) flight demonstations.

CDTI studies were continued in the 1970's and 1980's to investigate potential applications that could increase airport capacity, reduce controller stress and workload, and enhance safety of flight. These studies used simulations of the proposed Threat Alert and Collision Avoidance System (TCAS), Mode S radar, and other data link systems. Based on these simulations, traffic displays were postulated and tested under simulated traffic conditions. Pilots and controllers participated in these tests, and much was accomplished in understanding the relative vehicle dynamics, the human factors of traffic displays, and the potential of CDTI to provide benefits. The studies also revealed potential problems such as increased pilot and controller workload and possibilities of traffic flow instability, secondary conflicts, and pilot distraction. The results of these studies are discussed further later in this report.

Airborne traffic displays were developed as optional equipment during the TCAS II program. The functions of these displays are to:

1. Aid in visual acquisition of adjacent traffic;

2. Discriminate threat traffic from any other traffic;

3. Provide range and bearing information on adjacent aircraft; and

4. Instill confidence in the resolution advisories.

Installation of TCAS II has begun and will extend through 1992 for air carriers. In all cases, installation plans include some form of the TCAS traffic display. Thus, via the TCAS Program, the inclusion of a cockpit display of adjacent traffic has become a reality. It is now appropriate to investigate how this new capability should be exploited.

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TCAS II - CDTI Opportunity

The air carrier fleetwide installation of TCAS II systems will provide fleetwide display of aircraft traffic directly to the flight crew. This airborne traffic sensing and cockpit display of traffic are two of the primary elements required to mechanize the CDTI concept. It remains to be determined (a) how this traffic information is to be used by the flight crew, if at all, other than for collision avoidance prevention, and (b) what additional features or system sub-elements are needed to supplement the existing TCAS II information to provide the mechanism for realizing the CDTI applications.

Many pilots who have seen the TCAS display have concluded that there is now the immediate potential for the flight crew to assist the air traffic controller in the traffic management process via several CDTI application ideas. This has long been a vision of aviation researchers who have studied the CDTI concept. The previous CDTI research indicated that there could be airspace capacity benefits from using the CDTI to provide tighter spacing and relative positioning control of adjacent aircraft.

Today, there is an increased flight efficiency motivation for exploring these concepts further because there in a increasingly critical demand to create more airspace capacity and to reduce in-flight delay in the National Airspace System. Loss of airspace capacity is costing this nation's air transportation industry millions of dollars annually, and with increased demand for flight, these costs will continue to rise. Thus, if the CDTI concept can be used to increase airspace capacity and reduce delays in addition to providing increased safety and controller productivity, this opportunity should be quickly pursued and capitalized upon.

Industry requested a study to determine if TCAS-CDTI could be used in a cooperative manner with ATC to increase terminal capacity. The intent of this project is to involve the FAA ATC and Flight Standards organizations fully. Their participation in the development of any application would provide project guidance, maintain the safety factor and insure any concept acceptance that might evolve.

Project Objectives

The objectives of Phase I of this project has been to identify and to evaluate potential applications of a TCAS II-derived CDTI that will improve capacity in terminal areas during both marginal Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) [1], as well as enhance the safety of flight. This included the following:

1. Identify procedures and system requirements necessary to achieve the mechanization of the prospective CDTI applications;

2. Assess the current TCAS II configuration to see if it could meet these requirements; and

3. Define the necessary engineering, development, and testing remaining to be conducted for CDTI application realization.

The objective of Phase II of this project will be to use the evaluation results of Phase I to specify TCAS design modifications, application testing requirements and controller-flight crew procedural changes to realize the potential airspace capacity and safety benefits.

PROJECT OVERVIEW

TCAS II - CDTI Opportunity:

- Advent of TCAS II Implementation Provides Display of Adjacent Traffic in the Cockpit

- Traffic Display May Allow Flight Crew to Assist Controller in Traffic Management Process

- Previous Research Indicated NAS Capacity Benefits May Exist from CDTI

- TCAS Implementation May Afford an Opportunity to Realize These Benefits

Project Objectives:

- Evaluate Selected Applications of TCAS II Derived CDTI for Improving Terminal Capacity in IMC

  - Identify Necessary Procedures

  - Identify System Requirements

- Use Evaluation Results to Specify TCAS Design Modifications, Applications Testing Requirements, and Controller/Crew Procedural Changes to Realize Potential Benefits

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Project Scope

During Phase I of this effort, the following items were addressed:

1. The Operations Team, consisting of flight transportation industry and government personnel, identified five specific terminal area CDTI applications which would subsequently be evaluated by the Technical Team. The results of the Operations Team work, along with associated issues that require attention, are summarized in Section II of this report.

2. The Technical Team, consisting of engineers who have had experience with the design, development and testing of TCAS and/or CDTI concepts conducted the following sequence of evaluations:

   a. The previous research that had been conducted on cockpit traffic displays and on the design of the TCAS II system were reviewed. Information that was relevant to the CDTI applications proposed for this effort was extracted and summarized; this appears in Section III.

   b. The existing TCAS II design elements - sensor accuracy and coverage, signal filtering, threat logic software, and display generation - were reviewed with respect to the selected CDTI applications. The results of this review are summarized in Section IV.

   c. In review of the TCAS II design, it was determined that this design must be enhanced somewhat to fulfill the requirements for certain selected CDTI applications. In addition, further studies are required to assess flight safety and workload and to specify flight crew and controller procedures and training as part of realizing the mechanization of the CDTI applications. These further requirements are summarized in Section V.

3. As a result of the above evaluation, a 33-month Phase II effort is being recommended to provide the engineering, development, and testing to support achieving the CDTI applications. The specific aspects of the Phase II effort recommended are presented in Section VI. Phase II will include further detailed analyses and display enhancement investigation. Successful concepts will be integrated into a full workload aircraft simulator system. The potential applications will be objectively investigated via this simulation over a range of IMC traffic situations. An experimental CDTI display system, using modified TCAS II production equipment and operating procedures, will be established based upon the simulation results. This system will be integrated into an aircraft for flight investigation. Flight tests will be conducted in simulated IMC traffic situations and will involve both pilots and controllers. The results of Phase II will be proposed operational procedures, minimum CDTI performance requirements, and system certification guidelines to mechanize concepts that have demonstrated an improvement to traffic capacity in the terminal area while maintaining an equivalent level of flight safety.

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PROJECT OVERVIEW (CONT')

Project Scope:

Phase I:

- Identify Specific Terminal Area CDTI Applica'ions
- Review Previous CDTI Research; Determir₄ Relevance
- Assess Existing TCAS II Sensor, Software, and Display Performance Relative 'o CDTI Applic₄tions
- Where Necessary, Specify TCAS/CDTI Development Effort Needed to Establish System F ·formance to Meet CDTI Application Requirements
- Summarize Results in Feasibility Report and Provide Recommendations to Meet Project Objectives.

Phase II:

- Provide Required Engineering, Davelopment, and Testing to Support CDTI Applications as Recommended in Phase I

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II. PROPOSED POTENTIAL TERMINAL AREA APPLICATIONS

This section presents the suggested applications of the TCAS-based CDTI in the near terminal area as proposed by the Operations Team. These suggestions are followed by a list of critical questions associated with each application that must be answered to allow the air traffic controller and the flight crew to use the CDTI to complement the traffic management function. It is recognized that TCAS provides only a limited view of the overall traffic picture to the aircrew. Nevertheless, industry has proposed that the efficiencies of flight operations and air traffic control can be enhanced through the more complete sharing of information between the aircrews and the controllers without necessarily changing their respective responsibilities.

As stated earlier, the TCAS technology places a traffic display in the cockpit and a new, redundant system for separation assurance in the National Airspace System (NAS). Flight crew experience during the Limited Installation Program (LIP) indicated that pilots will monitor nearby traffic with this display [2,3]. With regard to possible CDTI applications, a process must take place which institutionalizes the associated procedures in both air traffic and flight standards to allow pilots to use the display to gain NAS efficiencies. At the same time, safety should be enhanced by allowing the pilot to use the CDTI to monitor the air traffic management process.

The three-step approach to CDTI investigation suggested by the Operations Team was as follows:

1. Identify procedures that can be accomplished in the short term with minimum to no enhancements to current production TCAS units.

2. Identify procedures that can be used in the intermediate term with minor modifications to current TCAS technology.

3. Identify procedures that can be used in the longer term and which may require extensive modifications to the TCAS system.

At no time should the primary TCAS function of collision avoidance be compromised. Also, the Operations Team recommended that steps be taken now (a) to implement the short term procedures as airline fleets begin to equip with TCAS sets, and (b) to begin action now on all procedures which show promise for capacity and safety enhancement.

Five terminal area applications of using the TCAS for CDTI purposes were suggested; they are:

1. Improve the speed and reliability of (a) visual acquisition during the transition from IFR to VFR, and (b) transfer of the responsibility of separation from controller to pilot. This is considered a passive application in that no procedural changes are required, and that the TCAS display can be utilized directly in its present format.

2. Reduce departure separation during IMC.

3. Provide in-trail following (station keeping) to reduce unnecessary spacing and to reduce interarrival error.

4. Enable parallel approaches in IMC to closely spaced parallel runways.

5. Enable converging approaches under lower ceilings and visibilities than is permitted today.

Each of these applications is now discussed.

Application No. 1. Improve Visual Acquisition

Concept

Visual separation is applied by air traffic control to enable a number of capacity enhancing terminal procedures. These include parallel approaches to very closely spaced runways, converging approaches, and closely spaced departures. Visual separation may be used by a controller who sees both aircraft. More frequently, however, visual contact is established by one of the pilots and he is instructed to maintain visual separation from the other aircraft. These procedures are terminated when the pilots begin having difficulty establishing or maintaining visual contact due to meteorological obstructions to vision. The TCAS traffic display can be used to establish more easily the visual contact with another aircraft, thus increasing the amount of time that visual separation procedures may be used.

Scenario

While being vectored to the final approach course, a pilot receives a radar traffic advisory on a flight making an approach to a parallel runway. Haze under the clouds restricts in-flight visibility to just over three miles. By referring to his traffic display, the pilot is able to focus more precisely his visual scan for sighting the traffic. He locates the traffic and reports such to ATC before radar separation is lost. The tower is able to continue using two runways for landing at the airpor

Closer in, as both aircraft are on approach, widely scattered low clouds intermittently obscure the other aircraft. The TCAS display once again aids in the quick re-acquisition as the airplane emerges from behind the small cloud. While this pilot might have reported losing visual contact without the display, he is confidant of being able to carry out his separation responsibility because of the continuous display of his traffic.

Product

The program will facilitate this use of the TCAS traffic display for both pilots and controllers. There will be an attempt to quantify the effect of this use of the display during the upcoming flight evaluation of TCAS in the airline fleets (TCAS Transition Program - TTP).

Benefit

Visual approach criterion can be used more often when there are lower visibility conditions. This will increase terminal capacity and overall flight safety.

PROPOSED POTENTIAL
TERMINAL AREA APPLICATIONS

1. Improve the speed and reliability of visual acquisition during the transition from IFR to VFR and transfer of responsibility of separation from controller to pilot (Passive application)

2. Reduce departure separation.

3. Provide In-trail following (station keeping) to reduce unnecessary spacing and to reduce interarrival error.

4. Enable parallel approaches to closely spaced parallel runways.

5. Enable converging approaches under lower ceilings and visibilities than permitted today.

APPLICATION DESCRIPTION

NO. 1 IMPROVE VISUAL ACQUISITION

Concept:
- Visual Separation Applied by ATC to Enhance Capacity of Terminal Procedures
- Visual Contact Established by Own Flight Crew; They are Instructed to Maintain Visual Separation from Other Aircraft.
- Procedures Terminated when Own Crew Begins to have Difficulty Maintaining Visual Contact.
- TCAS Display can be Used to Establish and Maintain Visual Contact.

Scenario:
- During Vectoring to Final Approach, Own Pilot Receives Advisory on Flight Making Approach to Parallel Runway.
- Haze Restricts Inflight Visibility to Just Over 3 NmI.
- By TCAS Reference, Own Pilot Precisely Focuses Visual Scan on Traffic; He Locates Traffic and Established Positive ID with ATC; He Accepts Responsibility for Separation According to VFR.
- Tower Able to Continue Using Two Runways for Landing

Benefit:
- Visual Approach Criterion can be Used More Often (In Lower Visibility Conditions). Terminal Capacity and Safety are Improved.

Application No. 2. Reduction of Departure Separation

Concept

In today's environment, successive departures are separated by standard radar criteria during IMC. The distance can be reduced to 1 mile if departure courses diverge by 15 degrees or more. This requirement equates to several minutes delay and can significantly reduce departure capacity causing delays at the departure airport. By observing a previous departure on the TCAS display, a pilot could depart behind another aircraft as soon as he observed an altitude increase.

Scenario

Own pilot is cleared into position behind a departing aircraft. Upon seeing the altitude readout of the preceding aircraft begin to increase, he informs the tower who then clears the specified aircraft for takeoff. Own pilot then maintains a specified distance from the preceding aircraft using the TCAS display. This can be used by successive departures from the same runway or by simultaneous departures from parallel runways.

Product

The program will determine (a) the minimum departure spacing required and if that can be achieved by the use of the TCAS display, and (b) if TCAS II is accurate enough to insure that the required separation intervals are maintained.

The program will also propose procedures for inclusion in Air Traffic Control Handbook 7110.65 and the Airman's Information Manual, Part 1.

Benefit

By using this technique to reduce departure separation in IFR conditions, the departure capacity should substantially increase.

APPLICATION DESCRIPTION

NO. 2 REDUCE DEPARTURE SEPARATION

Concept:

- In Current IFR Environment, Successive Departures are Separated by Standard Radar Criterion or 1 Nmi if Courses Diverge by 15 deg.

- Current Criterion Reduces Departure Capacity and Causes Delay

- By Observing Previous Departure on TCAS Display, Own Crew Can Depart as Soon as Altitude Increase Observed.

Scenario:

- Own Crew Cleared Into Position behind Departure; Own Crew Establishes Positive ID and Sees Other Altitude Increase.

- Own Crew Informs Tower; Tower Clears Own Crew for Takeoff.

- Own Crew Maintains Specified Distance from Other Aircraft Using TCAS Display

- TCAS Provides the Standard Protection Volume

Potential Benefit:

- Departure Capacity in IFR Could Substantially Increase.

CDTI DISPLAY
Departure Scenario

Bearing Error ± 9°

11
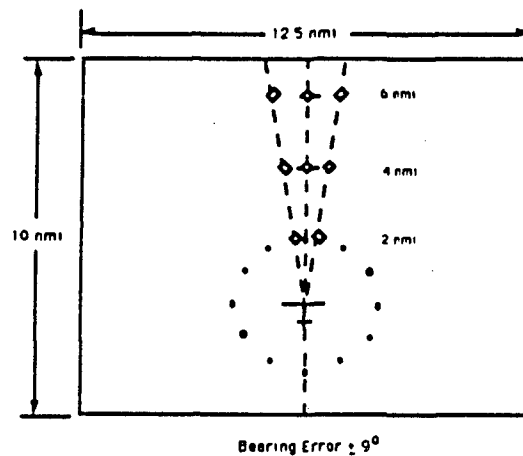
Application No. 3. In-Trail Following to Reduce Inter-arrival Error

Concept

While runway occupancy and wake turbulence separation are generally considered to limit the capacity of a runway, as a practical matter, the inter-arrival spacing error actually limits the achieved arrival rate. Variability in spacing between arrivals causes aborted landings on the short side, and wasted runway time on the long side. For at least twenty years, engineers have sought a way to capture this wasted resource with spacing algorithms for controller's use. This application of TCAS would involve the pilot in the spacing control loop, using the traffic display to accomplish the controller's spacing objective. By referring to the traffic display or enhancements up to and including speed guidance, pilots would exercise control over the interval either in distance or time as requested by ATC.

Scenario

The pilot receives radar vectors from ATC to intercept the final approach course. Whenever warranted by demand, a desired spacing interval at the threshold or final approach fix behind the preceding arrival will also be issued by approach control. The pilot identifies the aircraft ahead by azimuth, distance, and altitude as called by ATC and verified on his traffic display. He then modifies his speed, while above 1000 feet AG, as necessary to establish the desired interval and then to match the speed profile of the aircraft ahead.

With respect to the TCAS display design:

1. The current production TCAS units only show distance to other airplanes on the traffic display. It would not be possible for pilots using this basic display to do more than fly to an approximate target distance interval.

2. Enhancements to the basic display might include a predictor on the ownship symbol, and a relative velocity vector on the target aircraft. These vectors could be controllable to the desired time or distance spacing.

3. A further enhancement would track the speed profile of the aircraft ahead and provide a speed command on the EADI to capture and maintain the desired time interval.

Product

The program will provide descriptions of various options for performing the final approach spacing function and the performance of each.

The program will also propose procedures for inclusion in Air Traffic Control Handbook 7110.65 and the Airman's Information Manual, Part 1.

Benefit

It is currently estimated that from 5% to 25% of runway capacity is lost because of spacing gaps between sequential aircraft. A significant portion of this loss may be recovered by aircraft self-spacing control. The flight crew would use the CDTI display to remove large initial gap errors as directed by the controller.

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APPLICATION DESCRIPTION

NO. 3. REDUCE UNNECESSARY SPACING AND INTERARRIVAL ERROR

Concept:

- On Final Approach, Inter-Arrival Spacing Error Limits the Achieved Arrival Rate.
- Variability in Spacing Causes Aborted Landings (Too Close) and Wasted Runway Time (Too Far)
- Use of Spacing Algorithms and Displays to Remove This Error have been Extensively Tested via Cockpit Simulation.
- TCAS Display May Provide Early Mechanism to Remove Part of this Error.

Scenario:

- Own Crew Receives Clearance to Intercept Final Approach Course.
- When Warranted by Demand, Desired Spacing Interval Behind Preceding Arrival Issued by Approach Control.
- Own Crew Identifies Other Lead Aircraft on TCAS Display and Sets Desired Spacing Distance.
- Own Pilot Uses TCAS Display with Enhancements to Close and Maintain Desired Spacing to Remove Most of Interarrival Error.

Potential Benefit:

- Currently Estimated that 5% to 25% of Runway Capacity is Lost Because of Spacing gaps between Sequential Aircraft.
- A Significant Portion of this Loss may be Recovered by Simple Aircraft Self-Spacing Control.

CDTI DISPLAY
In-Trail Following Scenario
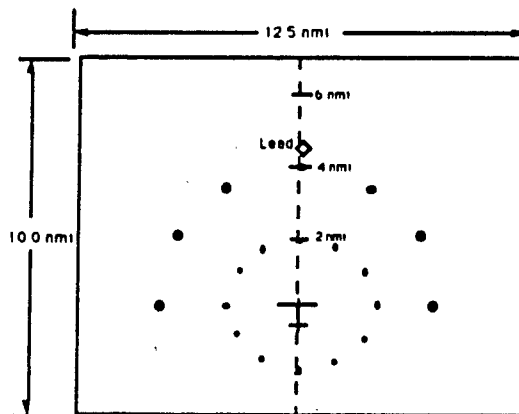
Application No. 4. Closely Spaced Parallel Approaches

Concept

Independent parallel ILS approaches may be conducted in IMC with runway spacings as little as 4300 feet using current procedures. There is work under way to expand this procedure to runways with as little as 2500 - 3000 feet lateral spacing using new radar technology and a system known as the Precision Runway Monitor (PRM) [4].

Dependent parallel ILS approaches can currently be made if runways are at least 2500 ft apart if diagonal separation between aircraft on adjacent approaches is maintained to be at least 2.0 nmi. The FAA is currently investigating what the requirements are to reduce the lateral separation down to 1000 ft and the diagonal stagger down to 1.5 nmi or less [5].

This application of TCAS is an alternative for providing the safety required to conduct parallel ILS approaches to the current minimum spacing for wake turbulence independence, namely, 2500 feet. After standard radar separation and altitude separation are lost during the respective "turn ons" to the final approach courses, separation would be provided procedurally through navigation on the localizers, backed up by TCAS resolution logic to prevent a collision hazard in the event of error or navigational blunder. The TCAS display could be used to help the flight crews maintain side-by-side positioning for independent approaches. It could be used to help the flight crews to maintain tight stagger position control during dependent approaches. Thus, in addition to providing flight safety, the TCAS display could be used for position control to enhance airspace capacity.

Scenario

The pilot receives ATIS information indicating parallel ILS approaches are in progress. He selects the terminal mode on the TCAS mode selector, and sets his radios for his ILS approach. The approach controller verifies the flight is TCAS equipped by reference to the equipment identifier on the flight strip (or electronic flight strip). Normal radar vectoring and altitude assignment place the aircraft on an intercept heading with clearance for the ILS approach.

The pilot notices another aircraft on his traffic display which, by reason of its position and altitude, appears to be making the adjacent parallel approach. At the normal time, this traffic triggers a traffic advisory (TA), and it becomes yellow on the display. Both pilots fly their ILS approaches with modified instrument scans. The TCAS is used by Own pilot to monitor and to adjust Own aircraft position relative to the adjacent aircraft. As long as no separation hazard exists, the TCAS remains silent throughout the approach.

If, during the approach, one of the aircraft blunders toward the other, the TCAS resolution logic is triggered either by the Tau or absolute distance criterion, directing the pilot either to climb or not climb as necessary to ensure separation. The pilot may have noticed the situation developing on the display, but it is not necessary that he do so. He is at least aware that another aircraft is on the other approach. When the advisory sounds, the aircraft response begins within five seconds as was confirmed during the TCAS LIP flights. If a climb is required, the pilot calls a missed approach and proceeds as depicted on the approach chart or as directed by ATC. If the other aircraft is pulling overhead, TCAS advises not to climb and the pilot continues his approach.

PARALLEL APPROACH RULES AND ON-GOING PROJECTS
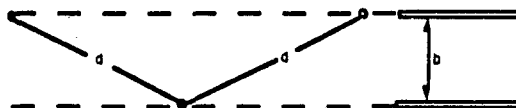
INDEPENDENT PARALLELS

- Parallel separation "b" must be at least 4300 ft apart

- FAA developing Parallel Runway Monitor (PRM) system to reduce separations to range of 2500-3000 ft via improved surveillance.

DEPENDENT PARALLELS

- Parallel separation "b" must be at least 2500 ft apart and diagonal separation "d" must be 2.0 nmi on adjacent approaches.

- FAA projects examining reduction of parallel separations down to 1000 ft and diagonal stagger down to 1.5 nmi or less.

APPLICATION DESCRIPTION
NO. 4. ENABLE CLOSELY SPACED PARALLEL APPROACHES
(Independent Approaches)

Concept:

- Currently, Independent Parallel ILS Approaches may be Conducted in IMC with Runway Spacings down to 4300 ft.

- On-going Parallel Runway Monitor (PRM) Project Examining Feasibility of Reducing Runway Spacing down to 2500-3000 ft.

- After Turn onto Final Approach Courses, Separation can be Provided Procedurally Through Localizer Guidance Possibly Backed up by TCAS Resolution Logic to Prevent Conflict Hazard in the Event of Pilotage Blunder.

Scenario (Independent Approach)

- Own Crew Receives ATIS Information Indicating Parallel ILS Approaches; Selects Terminal TCAS Mode; Sets up Aircraft Systems for ILS Approach.

- Own Crew Identifies Other Aircraft on TCAS Display Which is Determined to be Making Adjacent Parallel Approach; Traffic Advisory (TA) Triggers at Normal Time.

- Both Crews Fly Their ILS Approaches with Unmodified Instrument Scans; TCAS Remains Silent Throughout Approach.

- If One Aircraft Blunders During Approach, Revised TCAS Logic Would be Triggered; TCAS Advisory Determines Whether Own Aircraft Should Fly Missed Approach or Continue Landing.

Potential Benefit:

- Of Top 100 Airports, 28 have or Plan to have Runways with Spacings of 2500-4300 ft

- Arrival Capacity Doubled over Single Runway Capacity in IFR

Product

The program will produce sufficient data through simulation and flight test to determine the viability of the parallel approach concepts to pilots, air traffic personnel, and certifying authorities.

The program will produce logic for TCAS II units to support the parallel operations as proposed.

The program will also propose procedures for inclusion in Air Traffic Control Handbook 7110.65 and the Airman's Information Manual, Part 1.

Benefits

For independent approaches, of the top 100 airports, 28 have or plan to have runways with spacings of 2500 - 4300 ft. Using parallel runways, the arrival capacity is doubled over a single runway's capacity during IMC [5].

For dependent approaches, of the top 100 airports, 27 have or plan to have parallel runways with spacings of 1000 - 2500 ft. Parallel operations have a 39% capacity improvement over single runway operation with the diagonal set at 2.0 nmi. This improvement increases to 54% when the diagonal is reduced to 1.5 nmi [5].

APPLICATION DESCRIPTION

NO. 4 . ENABLE CLOSELY SPACED PARALLEL APPROACHES

(Dependent Approaches)

Concept:

- Currently, Dependent Parallel ILS Approaches may be Conducted in IMC with Runway Spacings down to 2500 ft.

- Diagonal Separation must be 2.0 Nmi on Adjacent Approaches.

- On-going Projects Examining Feasibility of Reducing Runway Spacing down to 1000 ft and Diagonal Separation down to 1.0 Nmi.

- TCAS Display can be Used to Provide Possible Blunder Protection and to Close on Desired Diagonal Separation.

Scenario: (Dependent Approach)

- Own Crew Sets Up and Selects TCAS Mode for Parallel ILS Approaches.

- Own Crew Sees Other Aircraft on Adjacent Approach on TCAS Display; Desired Diagonal Spacing Interval Issued by Approach Control;

- Own Pilot Uses TCAS Display with Enhancements to Close and Maintain Desired Diagonal Spacing.

Potential Benefit:

- Of Top 100 Airports, 27 have or Plan to have Parallels Runways with Spacings of 1000-2500 ft.

- 39 % Capacity Improvement over Single Runway with Diagonal at 2.0 Nmi; 54 % Improvement with Diagonal at 1.5 Nmi.

CDTI DISPLAY
Parallel Approach Scenario

17
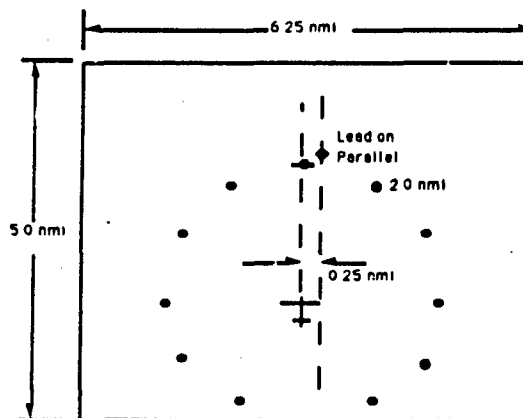
Application No. 5. Converging Approaches

Concept

Converging approaches are conducted today in IMC but under relatively high minimums due to the fact that aircraft must maintain TERPS separation criteria plus three miles in the missed approach area. In some locations, minimums are as much as 500 ft. higher than they would be for the stand-along approach when converging approaches are published and as much as 1000 ft. and 3 miles for non-Part-97 procedures. In many instances, this almost negates the benefits of the procedure. By using the TCAS displayed traffic, pilots can monitor the aircraft on the converging approach to maintain the appropriate stagger so that if a go-around becomes necessary, separation is insured. Furthermore, the crews will be able to monitor the other aircraft during the missed approach.

Scenario

The pilot is cleared for a converging approach and told that there is another aircraft executing a simultaneous approach to another runway. The pilots acquire one another on their TCAS displays and adjust speeds to remain relatively staggered. To do this, it may be necessary to enhance the TCAS display with a ghost target of the other airplane. Should it become necessary to go around, Own's crew can monitor the Other aircraft on the display and maintain the appropriate spacing.

Product

The program will produce sufficient data through simulation and flight test to determine the viability of the concept to pilots, air traffic personnel, and certifying authorities.

The program will produce logic for TCAS II units to support the operation as proposed.

The program will also propose procedures for inclusion in Air Traffic Control Handbook 7110.65 and the Airman's Information Manual, Part 1.

Benefits

Of the top 100 airports, 58 are candidates for dependent converging approaches. Allowing dependent converging approaches in IMC will produce about 8 aircraft/hour increase in runway capacity over that of single runway operation [5].

Of the top 100 airports, 33 are condidates for independent converging approaches. The capacity increase for independent converging approaches is about double that over the single runway operation [5].

APPLICATION DESCRIPTION

NO. 5. ENABLE CONVERGING APPROACHES TO PARALLEL OR CONVERGING RUNWAYS

Concept:

- Converging Approaches Conducted Today under Relatively High Minimums so Aircraft can Maintain TERPS Separation Criteria plus 3 Nmi in Missed Approach Area.

- Project Underway to Provide Ghost Projection on Controller's PVD of Aircraft on Adjacent Approach. Controller Objective is to Maintain 2 Nmi Separation between Aircraft Position and Ghost Position.

- Flight Crews can Use TCAS Display to Monitor Converging Traffic and to Maintain Appropriate Stagger; If Go-Around Necessary, Separation can be Assured.

- Flight Crew can Use TCAS Display to Monitor Other Aircraft During Missed Approach

Scenario:

- Own Crew Cleared for a Converging Approach and Directed to Execute a Staggered Spacing Behind Other Aircraft on Adjacent Approach.

- Own Crew Sees Other Lead Aircraft on Adjacent Approach on Enhanced TCAS Display; Own Aircraft Closes Up Spacing on Ghost Target or Adjacent Other Aircraft Directly.

- If Go-Around Necessary, Each Aircraft Monitors Flight of the Other.

Potential Benefit:

- Of Top 100 Airports, 58 are Candidates for Dependent Converging Approaches. Capacity Increase is About 8 Aircraft/hr over Single Runway Operation.

- Of Top 100 Airports, 33 are Candidates for Independent Converging Approaches. Capacity Increase is About Double over Single Runway Operation.

Application Requirement Issues

The TCAS system is designed to provide on-board protection against airborne collisions; that is, the TCAS is a device to provide an extra measure of flight safety to the individual aircraft. It is imperative that using the TCAS traffic sensor and display for CDTI applications not compromise this TCAS-established degree of safety of flight. In fact, use of the TCAS-CDTI for improved visual acquisition and parallel and converging approaches should enhance flight safety. This is one of the primary issues that has to be addressed during the process of developing each of the CDTI applications.

With regard to the functional design of the CDTI system, the other issues governing the direction of the engineering effort can be divided into three categories:

1. Surveillance and tracking - Here, it is required to assess whether the current TCAS II designs provide adequate surveillance reliability to ensure that the Other aircraft (whether it be Lead for in-trail following on approach or departure, parallel aircraft, or converging aircraft) is always displayed or that surveillance drop-out are not critical. The estimated position and velocity of the Other aircraft, as determined by the tracking algorithm, must be accurate enough to support the application. The antenna pattern must be sufficient to provide the spatial coverage required to include the geometry of the Other aircraft's relative path. Finally, it must be established how multi-path and other site dependent phenomena can affect the utility of each of the suggested CDTI applications. This may be especially important for departure control at busy airports with significant ground clutter.

2. Display - To use the TCAS to support the CDTI application, several technical items need to be addressed relative to the display design. The information content of the display (e.g., the position and relative speed of the Other aircraft relative to Own aircraft and the intended approach paths) must be shown to be adequate and easy to use. The image quality and update rate of the Other aircraft must be adequate to convey pilot confidence in using the information and to provide adequate information rate to allow acceptable aircraft position control. Display format, including size of the display, symbols used, choice of color, and placement of the symbols within the display need to be specified. Finally, the location of the TCAS display within the cockpit must be appropriate, relative to the pilot's primary scan and flight phase workload; for in-trail following on final approach, a heads-up display may be required.

3. Human Factors - Here, questions that will be addressed include those relative to the interface between the flight crew and the CDTI display, the communications protocols between the flight crew and the controllers, and the flight crew and controller training that must occur before the specific application can be exercised.

For each of these four issues, a series of questions can be posed. These questions serve to focus the investigation of CDTI concepts. Some important questions to be addressed in the subsequent study are now listed. Specific meaning of the terms used in these questions are explained later in this report.

Safety

1. What separation distances provide adequate safety margins to utilize each of the CDTI applications?

2. What CDTI display accuracy and operational procedures are necessary to meet these separation standards?

TCAS-CDTI SYSTEM REQUIREMENT ISSUES
THAT NEED TO BE ADDRESSED

1. Safety

2. Surveillance and Tracking

   - Reliability
   - Accuracy
   - Spatial Coverage
   - Site Dependence

3. Display

   - Information Content
   - Image Quality and Update Rate
   - Format - Size, Symbols Used, Color, Placement
   - Location within the Cockpit

4. Human Factors

   - Crew/CDTI Interface
   - Crew/Controller Communications Protocols
   - Crew and Controller Training

APPLICATION ISSUES AND QUESTIONS

AREAS OF CONCERN AND EXAMPLES OF EACH

Safety:

What CDTI display accuracy and operational procedure constraints are necessary to ensure meeting safe separation standards?

Tracking and Data Processing:

How do the current TCAS II limitations of antennae pattern volume of coverage, measurement error, and tracker algorithm affect the ability to utilize each of the five candidate applications?

Display Information Content and Location:

Do the current TCAS II display formats and cockpit locations support each application? If not, how should they be relocated or enhanced?

Human Factors:

What crew/controller communication protocol is required to initiate and conduct the different applications? What training is required to allow flight crews and controllers to use these applications?

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Tracking and Data Processing

1. How do the current TCAS II limitations of antennae pattern volume of coverage, measure-ment error, and tracker algorithm affect the ability to utilize each of the five candidate applications? Can additional filtering improve the tracker and display errors without introducing unacceptable lag error?

2. How do the TCAS tracking errors affect the information quality of the designated Lead aircraft and associated state information (e.g., trailing history dots)?

3. What basic tracking reliability requirements are necessary for each application? How is this Other aircraft bearing and altitude dependent? What surveillance coverage volume is needed?

4. For departure separation: Will tracking accuracy support parallel runway departures? What separation is required during IMC conditions? Do both aircraft need TCAS for this application? What are the effects of multipath? How does multipath off buildings degrade the display or cause the target to disappear? Will antennae diversity solve the problem of takeoff hiding the antennae? Will reflections near the ground unacceptably reduce signal strength? Is this application aircraft type dependent? What about track drop out? Is six second target coasting a problem? What about ground target filtering? Does traffic density cause confusion of which aircraft is the Lead?

Display Information Content and Location

1. Do the current TCAS II display formats support each application? If not, how should they be enhanced? Does the display location impact the use of CDTI applications?

2. How is Positive Identification established for the Lead or Other aircraft? Will an identity tag be necessary on the Other aircraft symbol for this purpose? What TCAS data processing is required to show identity, altitude, ground speed, and heading of the Other aircraft?

3. Would using a separate Other aircraft or Lead symbol or color marking be useful to maintain positive identification? Is such a modification necessary?

4. Are the current 2 nmi or 3 nmi range rings adequate for maintaining in-trail separation? Should an adjustable range ring or some in-trail following designator be added?

5. For Departure Separation: Is increasing altitude rate on Other aircraft adequate to provide Own crew with identification information to re-acquire Other aircraft during a busy takeoff period?

6. For In-trail Following: How can Lead's history dots be stored and displayed? How should the appropriate trailing distance be computed (ground or airborne?) and designated? Should Own aircraft's predictor vector be computed and displayed to assist in capturing the appropriate spacing? How can ground speed, acceleration and turn rate be measured and included? How can the nominal ground track be computed and displayed? How does the wake vortex (distance) separation constraint during final approach get converted to a time separation requirement previous to crossing the Final Approach Fix?

7. For Parallel and Converging Runway Approaches: Can extended runway centerlines be shown? How can separation distances between centerlines be set? How can the displays be anchored to the ground reference frame? Is a displayed "no-transgression zone" necessary? Are ghost targets necessary on Own aircraft's centerline?

Human Factors

1. What crew-controller communication protocol is required to initiate and conduct the different applications? What is the protocol for Own crew to communicate to the controller that it is TCAS equipped and able to utilize the specific CDTI application?

2. Are there runway and traffic scenarios that would cause confusion on the part of Own flight crew as to which aircraft is the Other/Lead aircraft? By what means does Own crew positively identify and maintain identity of Other or Lead aircraft?

3. What training is required to allow flight crews and controllers to use these applications?

4. Can these applications be utilized with partially TCAS-equipped aircraft, partially trained flight crews/controllers, and a spectrum of traffic display types?

5. How can the pilot be trained to weight appropriately the possibly conflicting goals of (a) capturing/maintaining a desired in-trail spacing, and (b) setting up and maintaining the appropriate landing speed?

Some of these questions have been addressed during this Phase I effort. Most of them, however, require more in-depth analysis of cockpit simulator and flight test results. These must be addressed during Phase II.

III. RELEVANT RESEARCH, DEVELOPMENT AND TESTING

It was important during this effort to review the research, development, and testing that had previously been conducted or was on-going relative to the TCAS Program and to various aspects of CDTI concepts. This was so that (a) previously well established technical results could be factored into defining the requirements for using the TCAS II as a CDTI system, and (b) documented previous research would not have to be repeated; this would save project development resources and time.

The previous and on-going work can be divided into two categories: TCAS development results and generic CDTI studies. Many aspects of the TCAS design process are specific to establishing and meeting the minimum operational standards, and they are not repeated here. However, three elements of the TCAS design are of importance to the CDTI applications in that they must be considered (a) when devising TCAS enhancements to implement the CDTI concepts, and (b) when developing the procedures for using the TCAS as a CDTI. These are:

1. Surveillance - As discussed in Section II, the accuracy, reliability, and volume of spatial coverage of the TCAS II surveillance and the associated accuracy of the tracking algorithm govern to what extent TCAS can be used for the five selected CDTI applications. The TCAS II surveillance system design is primarily the result of work performed at MIT Lincoln Laboratory.

2. Logic Design - The TCAS II threat detection and collision avoidance logic was primarily developed by the Mitre Corporation. Many aspects of this logic will have to be examined in terms of the software enhancement requirements for each of the CDTI applications.

3. Pilot Interface - The TCAS II display design format and other aspects of the flight crew interface were studied at both NASA Ames Research Center and MIT Lincoln Laboratory. Because the CDTI will require changes to the display format as well as development of flight crew and controller procedures, the lessons learned from this previous work are important.

Previous research in cockpit traffic displays focused to some degree on the in-trail following application. This research consisted of both analytical work and experiments conducted using cockpit simulation. During the 1980-84 time period, NASA Ames and Langley Research Centers both sponsored analytical studies and conducted a series of experiments to determine (a) what were the important elements that allowed pilots to use the CDTI for in-trail following, (b) how could the CDTI be mechanized, and (c) what benefits might be realized from CDTI implementation. Previously, in the mid 1970s, MIT Flight Transportation Laboratory conducted cockpit simulator studies that explored many terminal area applications of the CDTI.

The important learnings and the methods used for the TCAS development and CDTI research are summarized in this section.

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TCAS Surveillance Development - MIT Lincoln Laboratory [6]

TCAS conducts surveillance in one of two modes. If the Other aircraft has Mode S, then surveillance is done in Mode S. Otherwise, surveillance is done in Mode C. With a Mode-C interrogation, all aircraft that are not equipped with Mode S reply together which leads to a problem with synchronous garble. Mode S does not have a synchronous garble problem but there needs to be a way to determine the interrogation address of each nearby Mode S aircraft.

There are also other surveillance problems common to both modes including multipath, angle-of-arrival accuracy, and power level determination. Using top mounted antennas was one step toward combating multipath. TCAS was designed to use both a top and bottom antenna although most existing transponder installations use only a bottom antenna.

Dynamic receiver thresholding is also used to combat multipath. Whisper-shout is a technique that was developed to combat the synchronous garble problem. Interrogations begin at low power and suppress those transponders that have already replied during the sequence. It was found that whisper-shout not only stopped synchronous garble but also reduced multipath on the interrogation link. An interference-limiting function was built into TCAS that limits the interrogation-power product of the transmitter based on a local monitor of the interference condition.

Acquisition of Mode-S addresses was accomplished by having all Mode S transponders squitter at a rate of once per second. A squitter is a spontaneous transmission in the format of a reply which includes the address of the transmitter.

A four-element antenna was developed which measured angle-of-arrival to an accuracy of 8 degrees one sigma. These developments have become a part of TCAS II.

Current surveillance research is focused on the development of a Bearing Rate Accuracy Monitor (BRAM) which could be used with TCAS III. The concept is to filter range measurements during encounters to deduce the bearing rate independent of the angle-of-arrival measurement. A post encounter comparison could provide calibration of the antenna. The work is not yet complete.

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TCAS DESIGN AND TEST
Surveillance - Lincoln Laboratory

TCAS II

- Whisper-Shout to Combat Mode C Synchronous Garble
- Mode S Squitter to Establish Mode S Addresses
- Dynamic Receiver Thresholding and Diversity Antenna to Combat Multipath
- Four Element Angle-of-Arrival Antenna Accurate to 8 Deg (One Sigma)

TCAS III (Work in Progress)

- Bearing Rate Accuracy Monitor (BRAM) Filtered Range History Provides Bearing Rate Information

TCAS Logic Design - Mitre Corporation

MITRE has conducted considerable research to develop the present TCAS logic and explore TCAS applications. Portions of that research which are germain to the application under consideration are noted.

The primary logic to determine alerting thresholds to provide collision avoidance and desensitization schemes to eliminate false alarms has evolved over a decade of testing and development. The Phase I Operational Evaluation (Nov 81 - Mar 82) was conducted with TCAS installed in two Piedmont B-727 passenger-carrying aircraft with trained observers viewing the displays placed aft of the cockpit. Problems with the logic were detected and subsequently corrected. Piedmont Phase II (Mar 87 - Jan 88) had the TCAS in view of the pilots. Modifications were made to eliminate nuisance alarms and improve system performance. Two Limited Implementation Programs on United (Feb - Aug 89) and Northwest (Sept 88 - Mar 89) evaluated the results of previous logic modifications and measured operational encounter rates. Earlier work had predicted operational encounter rates on the basis of analytic traffic models and ground radar data.

An analysis was conducted of potential conflicts between TCAS resolution advisories and ground proximity warnings. For example, an aircraft descending with a high sink rate might receive a TCAS resolution advisory to continue descent below the altitude at which the ground proximity alarm would activate.

A System Safety Study was conducted of the use of TCAS under Instrument Meteorological Conditions including interaction with the Air Traffic Control System. The study analyzed the level of safety considering such things as the fraction of aircraft equipped and the potential for one TCAS directed maneuver to initiate an additional conflict.

A concept was developed for using a cockpit display of traffic as derived from a modified TCAS to support reduction of the separation minima for oceanic track systems. Cost benefits, alert rates, operational procedures, and implementation strategies were studied to verify the feasibility of the concept. [7]

An obstacle avoidance service using TCAS was explored. Information on the location of an obstacle would come from a Mode S transponder mounted on the object. A Mode S message could contain special information such as identity or presence of multiple objects. TCAS would generate obstacle advisories using special logic.

The TCAS logic as originally conceived, designed and implemented was intended to perform the single dedicated function of collision avoidance [8,9]. All components of that system, both hardware and software, were structured in a way that did not anticipate other applications. Nevertheless, the current logic, unmodified, can find use in other applications such as some of those investigated in this report. Minor display modifications and development of operational procedures may be all that is required. The display modifications would not change the collision avoidance logic, only the way that TCAS data is presented to the pilot. For other near-term and advanced applications the TCAS logic will have to be partitioned, restructured and revalidated. This is needed to enable application insertion, assure application isolation, eliminate redundant logic functions, and facilitate recertification after applications have been added to the system. In order to do this it will be necessary to 1) identify and separate functions that will be common to all applications (e.g. surveillance, vertical tracking, etc.), 2) design standard interfaces between functions and applications, 3) identify additional inputs needed by the applications and design the logic to handle them, and 4) define, where possible, standard output data and their formats for use in annunciation systems and displays.

TCAS DESIGN AND TEST
Logic Design - MITRE Corporation

- TCAS II

  - Logic design, simulation, and validation

  - Defined concepts for near-term TCAS-CDTI applications

  - Planned restructuring and partitioning of TCAS II logic and logic performance assessment from TCAS Transition Program data

- TCAS III

  - Logic design, simulation, and validation

  - Design using expert system approach to advance TCAS II logic

  - Conducting system safety analyses

- Related Research Germain to Development and Test of TCAS Applications

  - Determination of logic alerting thresholds and desensitization schemes

  - Evaluation of TCAS performance using ground radar and flight recorded data

  - Interaction of TCAS with GPWS and ATC in IMC

  - Use of TCAS for over-the-ocean spacing monitor

  - Use of TCAS for obstacle avoidance

TCAS DESIGN AND TEST
Logic Design - MITRE Corporation (Cont')

Constraints to Any TCAS Logic Modifications

- TCAS Logic Intended to Perform Single Dedicated Function: Collision Avoidance

  - All system components structured without anticipation of other uses

  - Unmodified or slight display modification may support other application

  - Display modifications would not affect CAS algorithm

- For TCAS Logic to Support Other Applications, It will Require Re-Partitioning, Re-structuring, and Re-validation

  - Enable application insertion

  - Assure application isolation

  - Eliminate redundant logic functions

  - Facilitate re-certification after applications added

- Requirements for TCAS Logic Re-design

  - Identify and separate common application functions (e.g., surveillance)

  - Design standard functions-application interfaces

  - Identify additional inputs, sources, and processing logic

  - Define standard output data and formats for annunciation systems and displays

TCAS Pilot Interface Studies - NASA Ames Research Center [10]

A full-mission night simulation of TCAS operations was conducted at NASA Ames with airline pilots serving as subject crew members. Twelve crews had TCAS available and four crews did not have TCAS available. Crews with TCAS advisories available visually acquired 116 of the 207 aircraft (56%) which triggered TCAS traffic advisories. Crews which did not have TCAS advisories available visually acquired 44 of the 88 aircraft (52%) which would have triggered TCAS traffic advisories. Some of the aircraft which triggered traffic advisories were obscured by clouds; however, these conditions were similar for both groups. One non-transponder target was visible to each crew near the outer marker on one approach. It was visually acquired by 3 out of 4 of the non-TCAS crews and 5 out of 12 of the TCAS crews. It was concluded that the probability of visual acquisition at night was the same with or without TCAS. The result is plausable because aircraft lights at night are visible and conspicuous well beyond the threshold of TCAS traffic advisories. The results do not apply during daylight when the average range at visual acquisition is inside the threshold of TCAS traffic advisories. (Most midairs occur during daylight VFR, and current simulators are unable to display the inconspicuous daylight targets that match the lower than one arc minute angular resolution of the pilot's eye.) Crews rated the usefulness of TCAS for aiding visual contact with a mean score of 8.8 out of 10.

Crews were observed to check their TCAS traffic display before accepting heading and altitude assignments. If a traffic conflict was detected, the crew would notify the controllers suggesting that they delay a turn until clear of traffic. In one instance, a crew detected an altitude deviation by another aircraft.

Crews reported a consistent increase in workload with TCAS which was considered acceptable. Pilots rated the addition of TCAS to the other flight duties as 7.4 on a 10 point scale from "very distracting" to "not at all distracting".

TCAS DESIGN AND TEST
Pilot Interface Studies - NASA Ames Research Center

- **TCAS Human Factors Evaluation**
  - All tests conducted via full mission simulation
  - Developed training program model
  - Improved performance with new display format
  - Provided pilot performance constants for logic changes

- **Visual Acquisition (Night Simulation)**
  - Probability of visually acquiring aircraft that would evoke a TCAS advisory was same with or without TCAS.
  - Crews gave TCAS 8.8/10 rating as being very useful to aid in visual contact

- **Operational Error Prevention**
  - Crews observe TCAS before accepting heading and altitude assignments
  - If conflict detected, crews notify controller

- **Workload**
  - Consistent increase in crew workload with TCAS; however, increase considered acceptable
  - TCAS information not considered destracting

TCAS Pilot Interface Studies - MIT Lincoln Laboratory [11]

A mathematical model for predicting the probability of visual acquisition by pilots flying under daylight visual conditions has been developed and validated through flight tests conducted at Lincoln Laboratory. The model describes visual acquisition as a nonhomogeneous Poisson process in which the probability of visual aquisition per unit time is proportional to the solid angle subtended by the target. The model originated during testing of a proposed ground-based collision avoidance system. Subject pilots flew near-collision encounters and reported by radio transmission when visual aquisition occured. The paths of both aircraft were recorded by radar. By correlating speeds and distances with the times of sighting, the tests produced quantitative measures of visual acquisition performance, and validated the model.

Later, during testing for TCAS, six subject pilots flew a variety of missions that resulted in similar data for 66 near-miss airborne encounters. Using the TCAS, they visually acquired the threat aircraft in 57 of the 66 encounters. The median range of visual aquisition was 1.4 nmi. In five of the nine cases of acquisition failure, the subject aircraft was . . . high in response to a TCAS climb advisory that prevented sighting the threat passing below.

Another series of flight tests was conducted to determine pilot performance under unalerted search. A group of 24 general aviation pilots each flew a short cross-country flight while an intruder aircraft made unannounced passes over and under the subject-pilot's route to provide a target for visual aquisition. Data were collected in the cockpit by a safety pilot. Aquisition was achieved in only 36 of 64 encounters. The median aquisition range was 0.99 nmi. Based on these two test programs, the probability of visual aquisition under alerted search was 8.2 times greater than for unalerted search. The conclusion applies only to daylight visual conditions.

TCAS DESIGN AND TEST
Pilot Interface Studies - MIT Lincoln Laboratory

- **Near-collision encounter in daylight VFR**
- **Alerted Search - 6 Subject pilots - 66 encounters**
- **Unalerted Search - 24 Subject pilots - 64 encounters**
- **Andrews Visual Acquisition Model developed; Instantaneous acquisition rate proportional to visual angle subtended by target**
- **Acquisition probability 8.2 times greater for alerted search than for unalerted search**

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In-trail Following via CDTI - FAA-NASA Sponsored Analysis

Both the use of more automation and more involvement of the pilot in the air traffic control process are understood to be future needs for providing greater terminal area capacity. A joint FAA-NASA research project was conducted during the 1980-84 period to explore the uses of CDTI to meet these needs. One application that was focused upon was the use of the CDTI display by the pilot for non-vectored clearances relative to other traffic. Under this category are functions such as aircraft control into a traffic merge point and spacing along a route. In order to derive the control requirements for such functions, it was first necessary to understand the dynamics of merging and trailing aircraft [12].

Several questions were posed associated with the CDTI-based terminal area traffic tactical control concepts. These included:

1. What are the basic dynamic phenomena associated with independently controlled aircraft in a string?

2. What conditions would produce instability in the string?

3. What information does each pilot need (from CDTI and other sources) to merge his aircraft adequately into the string and then to maintain appropriate spacing?

4. What are the effects of measurement and display errors, wind shears, aircraft mixes, spacing constraints, and merge trajectories on the dynamics and control performance of the system?

5. What advantages does this concept have compared to ground-based control?

Six different cockpit simulator studies were made at NASA Langley and Ames Research Centers to produce data to analyze in-trail dynamics during this time period. In particular, the analysis addressed the first three questions and part of question 4 above.

A simplified generic CDTI display used for in-trail following is shown in the opposite sketch. Here, the pilot views the horizontal positions of his (Own) aircraft and the surrounding (Other) aircraft on the cockpit display. Own's position is indicated on the heading up display by the chevron symbol one-third the distance up from the bottom and centered laterally. The route path and other display features move continuously with respect to the Own symbol. Other aircraft are indicated by triangles. Own and Other aircraft symbols are preceded by vectors proportional in length to the ground speeds. They may be curved proportional to bank angle, and they produce a prediction of where each aircraft will be at a future time.
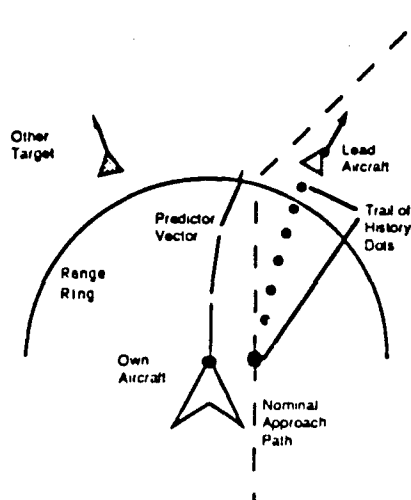
In the sketch, three different longitudinal separation criteria are depicted by the symbology. The separation criterion is the mathematical rule used as part of the CDTI display to indicate to the pilot what the desired separation should be between his and the Other leading aircraft. The criterion must establish a lower separation limit that is safe; yet, it must keep the aircraft close enough to provide for airspace and landing efficiency. The resulting implied acceleration commands must be within the normal limits of the aircraft. Finally, it should be possible to compute the criterion simply from available information and to display it to the pilot without ambiguity. The criteria depicted are:

1. Constant Range - This is shown by the constant range ring, and the pilot's objective is to steer Own aircraft so that the depicted range ring is on top of the Lead aircraft's current position. Current TCAS displays have fixed distance range rings.

PREVIOUS STUDIES - In-Trail Following via CDTI
Analytical Studies - FAA-NASA Sponsored

- Background
  - CDTI Research Sponsored by the FAA, NASA Langley and Ames Research Centers from 1980-1983.
  - Work Focused on Analysis of Dynamics and Control Requirements for Merging and Spacing of CDTI-Equipped Aircraft on Approach.
  - Six Different NASA Cockpit Simulator Studies made to Produce Data to Analyze In-Trail Following Dynamics. "Daisy Chain" of Following Aircraft Set Up for Studies.
  - Four Different CDTI Display Concepts Analyzed to Examine Stability, Pilot Workload, and Landing Efficiency - Constant Range, Constant Time Predictor, Constant Time Delay, and Acceleration Cue

- Studies Proved that there were no Particular In-trail Stability Problems but that Constant Time Delay or Acceleration Cue were Better than Constant Range or Constant Time Predictor in Terms of Improving Landing Rate

POSSIBLE DISPLAY FORMATS
FOR IN-TRAIL FOLLOWING

Other Target

Lead Aircraft

Predictor Vector

Trail of History Dots

Range Ring

Own Aircraft

Nominal Approach Path

Possible In-Trail Following Criterion

- Constant Range - Steer Own aircraft's appropriate range ring to be on top of Lead aircraft's current position.
- Constant Time Predictor - Steer Own's speed predictor vector to be on top of Lead's current position.
- Constant Time Delay - Steer Own's position to be on top of marked history dot.

2. Constant Time Predictor - This is the predictor vector that is in front of Own aircraft symbol; its length is the product of a time constant T_P and the measured ground speed V_g. It shows where Own will ideally be T_P seconds from now. The objective is to steer the tip of Own's predictor vector to be on top of the Lead aircraft's current position.

3. Constant Time Delay - This criterion consists of controlling Own to be where the Lead aircraft was T_D seconds earlier. This position is indicated on the CDTI display by an enlarged history dot. Own is steered so that the tip of the chevron symbol is on top of this moving dot.

A fourth separation criterion studied was called the Acceleration Cue. It modified the Constant Time Predictor criterion to include the effect of Own aircraft's measured acceleration.

Constant Distance Spacing. A simplified sketch of the CDTI display using constant distance spacing via range rings is shown on the next sketch. The nominal approach path is shown as the dashed line. Again, the objective is to control Own's speed and heading so that the range between Own and the designated Lead aircraft is held constant. The controller would instruct the pilot to close and maintain a particular separation. This concept has certain advantages:

1. Fixed range rings are a part of the current TCAS II display. Thus, pilot's will become quite familiar with using these rings to judge and partially control distance to other aircraft.

2. The range ring idea is simple to understand; they show exactly what the separation distance is now.

3. The range ring idea can show if large separation errors exist between consecutive aircraft; therefore, they can be used by the pilot to remove the greater part of these errors.

4. Because range rings are used currently, the constant distance criterion can most easily be adapted to the CDTI applications. The software enhancements required for this criterion would be the easiest to implement.

However, use of range rings for tight in-trail spacing control has inherent dynamics problems:

1. If the Lead aircraft slows down, this requires that Own instantaneously match this deceleration to maintain fixed distance spacing.

2. The instantaneous speed match causes a slowdown at an earlier range-to-go for Own aircraft.

3. Successive aircraft will slow down at increasing distances from the runway. Thus, using this criterion for a string of approaching aircraft would produce significant fuel penalties and operational problems. This would be caused by forcing aircraft to lower flaps earlier than normally required for landing in order to achieve the lower speeds required for spacing.

4. To meet final approach spacing of 2.5 or 3 nmi will require greater fixed distance spacing at speeds faster than landing speed. For example, if a 3 nmi separation is required behind an aircraft landing at 120 kt, then this separation will have to be 4.25 nmi when both aircraft are traveling at 170 kt.

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CONSTANT DISTANCE SPACING
(Range Rings)
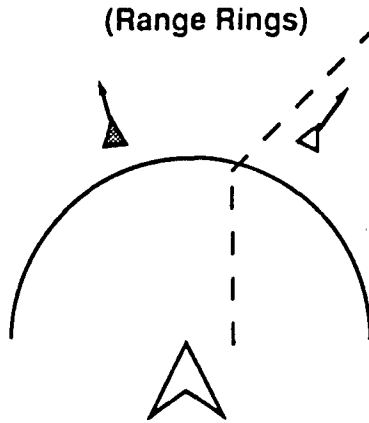
- Advantage: Current TCAS display format; simple to understand; useful to partially remove large spacing errors.
- Disadvantage: Requires instantaneous speed match of Lead aircraft to maintain fixed spacing; instantaneous speed match causes early slowdown for Own aircraft; Successive aircraft slow down at increasing distances from runway.
- Example: A 3 nmi separation on final at 120 kt would require a 4.25 nmi separation at 170 kt.

Some further unknowns about using this criterion are:

1. It is not known whether depicting the nominal route is required for in-trail spacing applications.

2. Adjustible range rings or range scale lines ("tick marks") may be required on the display to allow the controller and pilot to have flexible distance spacing, depending upon the speed regime of each pair of aircraft.

3. Another enhancement that may be necessary for certain applications is the addition of a display feature that shows the relative speed between Other and Own aircraft. This enhancement will govern how tight the spacing control can be maintained.

Constant Time Predictor and Acceleration Cue. For the Constant Time Predictor, the nominal spacing between two aircraft can be expressed as

$$r_{Nom} = r_L - r_O = V_O T_P$$

In this equation, r_{Nom} is the desired longitudinal separation distance, r_L and r_O are the longitudinal ranges traveled from some initial waypoint by the Lead and Own aircraft, V_O is the ground speed of Own, and T_P is the time constant. Note that the Federal Aviation Regulations specify minimum separations in terms of distances rather than times. Thus, the time constant T_P must be chosen so that the minimum separation specification at the slowest landing speed is not violated. Also note that V_O must be implemented as ground speed.

From the above spacing equation, it can be shown that the ideal speed of the Own aircraft is a lagged response with time constant T_P with respect to the Lead. The following figure illustrates the theoretical ground speed which would result as a function of range-to-go for a string of nine aircraft using the Constant Time Predictor criterion with T_P of 60 sec. Note that the lead deceleration causes successive slowdown of each following aircraft until the end where there is overcompensation causing increased landing speeds. Since the trailing aircraft must decelerate to their own landing speeds prior to touchdown, the higher landing speeds required to maintain the spacing time interval are actually never achieved. This results in an inherent loss in arrival capacity using this technique.
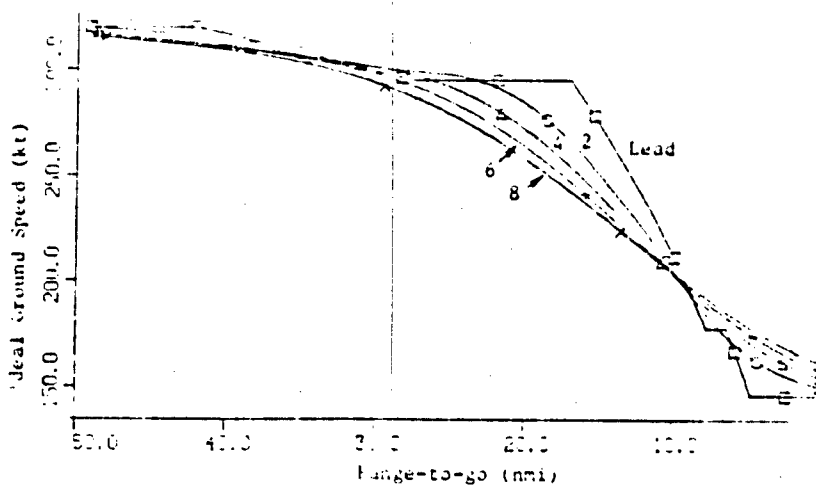

In the accompaning sketch, a generic Constant Time Predictor display is shown. Below it is a plot of successive ground speeds as a function of range-to-go taken from one of the NASA in-trail following experiments. Note the similarity in successive slowdowns for each aircraft in the string; this is very similar to the results predicted by the analysis.

A solution to the inherent slowdown effect of the Constant Time Predictor was to add an acceleration term to the separation equation [13], or

$$r_{Nom} = r_L - r_O = V_O T_P + 0.5 \, a_{MO} \, T_P^2$$

CONSTANT TiME PREDICTOR SPACING
## (Lead Vector on Own Aircraft = Vg * Tp)
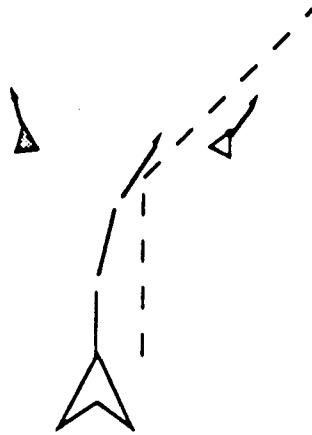
- Advantage: Easy to steer predictor vector to tip of Lead aircraft; easy to visualize effect of aircraft turn on future position.
- Disadvantage: Following aircraft slows down earlier and finishes going faster than Lead.

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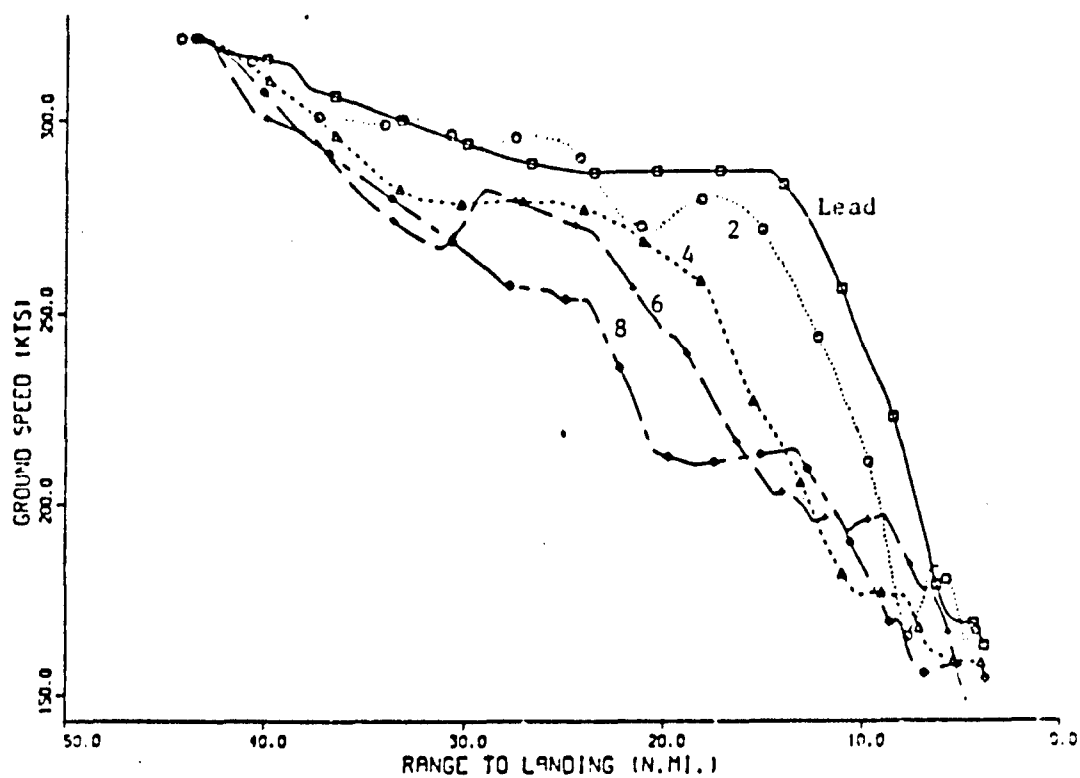
In this equation, a_{MO} is the measured acceleration of Own aircraft. This modification was referred to as the Acceleration Cue criterion. The figure below shows the ideal ground speed and separation between pairs of aircraft in a string when using this criterion modification. The trailing aircraft follow the lead much more closely than when the Constant Time Predictor criterion is used.

The advantage of using the predictor vector on the CDTI display is that it is easy for the pilot to visualize his future position and to steer around turns to reduce separation error. The disadvantage is that this criterion causes early slowdown of Own followed by late excessive speed. This disadvantage can be compensated by adding the acceleration term, but this is a more complex mechanization.

a) Ground Speeds

b) Separations

Range-to-go (nmi)

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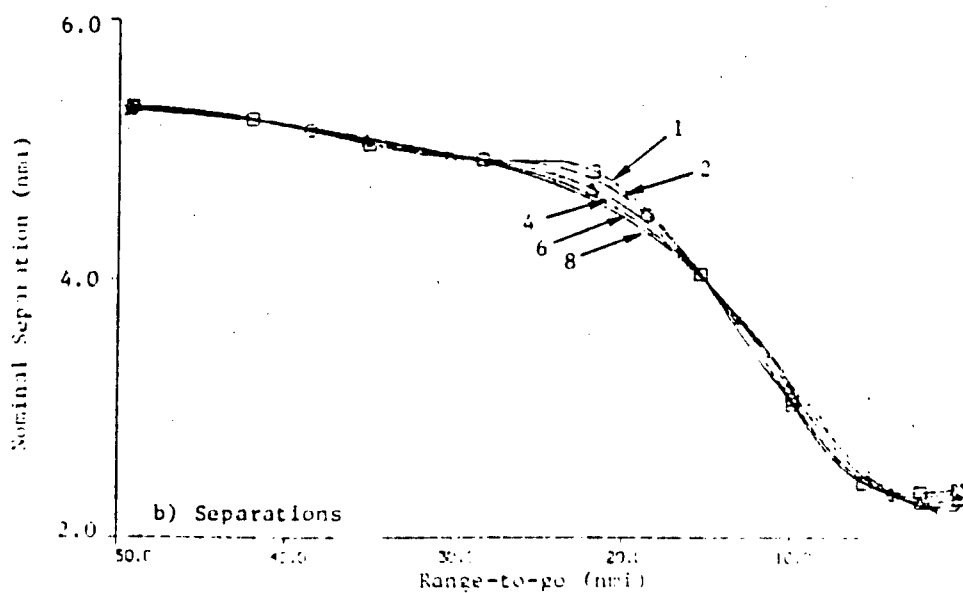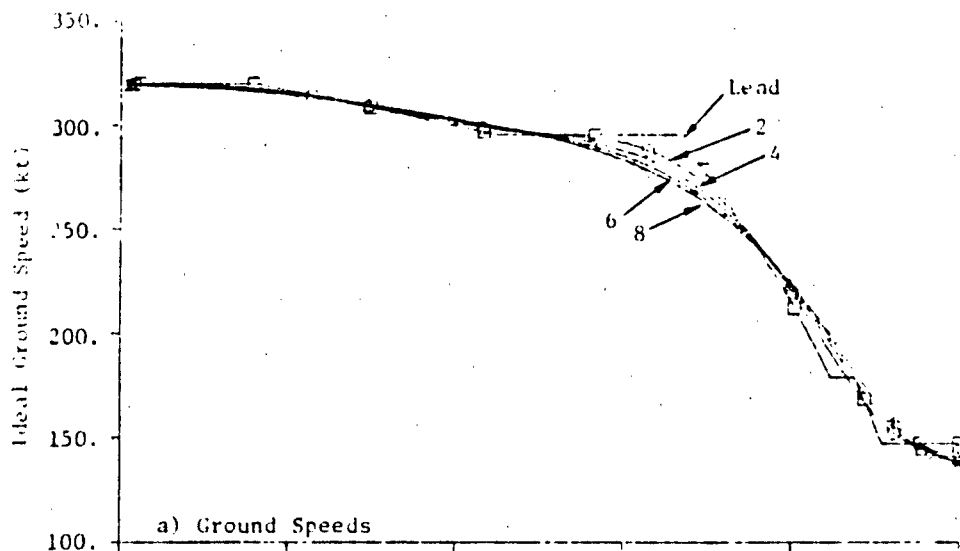
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Constant Time Delay. For this separation criterion, it is assumed that a trail of history dots is depicted on the display to indicate previous positions of the Lead aircraft. An enlarged moving history dot (or some other designator) can be used to indicate the ideal spacing of Own behind the Lead. The steering task consists of controlling Own to be where the Lead aircraft was T_D seconds earlier.

The advantage of the Constant Time Delay separation criterion is that the history dots provide an ideal trail and position for Own aircraft to follow. There is no inherent time delay in using this criterion. A disadvantage of this criterion is that the dots by themselves provide no turn indicator or deceleration cue for Own. Another disadvantage is that to implement this criterion requires storage of the Lead aircraft's position relative to the ground.

The plot on the opposite page shows ground speed vs range-to-go for a string of seven aircraft set up in another NASA in-trail following experiment using the Constant Time Predictor criterion. For these results, the time constant T_D was 60 sec. As can be seen, there is fairly good agreement between successive aircraft groundspeeds.

Either the Constant Time Delay or Acceleration Cue criteria produce acceptable spacing between successive aircraft in a string. The choice will have to be made based upon which is easier to mechanize using the TCAS traffic sensor. It may be advantageous to use features from each of the criteria for an overall display to facilitate tight in-trail spacing. This requires further TCAS design study in Phase II.

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CONSTANT TIME DELAY SPACING
(Own Aircraft on Lead Position of td sec Earlier)
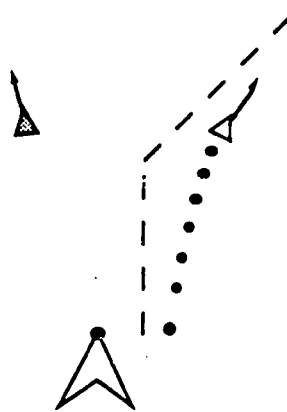
- Advantage: Provides the ideal trail and position for Own Aircraft to follow. No inherent time delay.

- Disadvantage: No turn indicator or deceleration cue for Own. Requires storage of Lead aircraft position relative to ground.

a) Every-other aircraft

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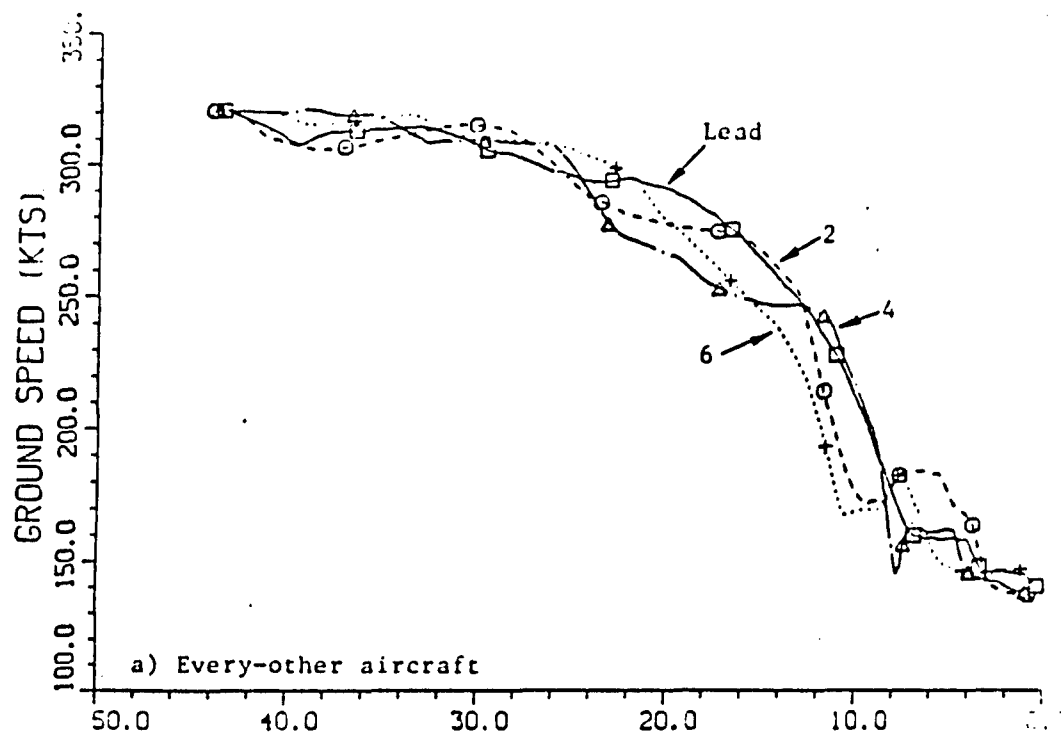
Additional Analytical Work. Beyond the cockpit simulator investigations of in-trail spacings via CDTI, NASA Langley and Ames sponsored further analysis concerning (a) how the CDTI display could be implemented using TCAS II and other traffic information sources, and (b) some of the issues associated with filtering the surveillance data to produce the traffic display.

Various estimation problems were addressed. These included:

1. The performance and choice of gains for range-bearing data processing in a Cartesian coordinate frame using alpha-beta filters;

2. Range measurement filtering;

3. Quantized altitude measurement filtering including the Level Occupancy Time filter; and

4. The effect of the encounter geometry including that of turns, climbs, and descents of one or both aircraft.

These results were all applied to the problem of generating the CDTI display to show the relative position and velocity of adjacent traffic plus the Lead aircraft prediction vectors, history dots, etc.

Another effort was to develop a comprehensive digital simulation model of the enhanced TCAS II system which was being considered as a traffic sensor for flight testing of CDTI concepts. This model was based upon characteristics of either the Bendix or Dalmo Victor (now Honeywell) prototype TCAS systems. The model was subsequently used in NASA cockpit simulation studies and Monte Carlo estimation error analyses [14].

PREVIOUS STUDIES - In-Trail Following via CDTI
Analytical Studies - FAA-NASA Sponsored

- Various estimation problems analyzed

  - Horizontal X Y filter performance
  - Range filters
  - Altitude filters including Level Occupancy Time filter
  - CAS geomtry impact
  - CDTI applications - target prediction vectory error performance

- Comprehensive digital simulation model of enhanced TCAS II - CDTI traffic sensor developed

  - Based on Bendix and Sperry-Dalmo Victor prototype systems
  - Model used in NASA cockpit simulation studies and Monte Carlo estimation error analysis studies

CDTI Cockpit Simulator Research Emphasizing In-trail Following - NASA Langley [15,16]

NASA Langley has conducted considerable research on CDTI system concepts, the majority of which has involved the in-trail following task. The simplest traffic display used there was an electronic navigation display oriented track up in the weather radar location with map features rotating and translating about a fixed ownship symbol. Traffic was displayed relative to the ground, with the traffic remaining fixed relative to the map between updates which occurred at four second intervals. Later, the updates were reduced to one second intervals.

Pertinent findings included the following: Distance spacing criteria is of limited use for descending and decelerating approach situations. The trailing aircraft is forced to decelerate at the same time as the lead aircraft rather than at the same point in space. For three mile spacing, the trailing aircraft would reach approach speed three miles earlier than desired. Some type of cue that Lead aircraft is decelerating turns out to be more important than display size or sensor accuracy. It is very difficult for pilots to detect a change in spacing, and once spacing is lost on final approach, it cannot be regained. Display of Lead aircraft groundspeed and relative predictors of Lead position have proven useful in this regard. It was found to be important that traffic be updated at the fastest possible rate which ended up as a one second interval.

To extend the utility of station-keeping further out on the approach, a constant time-delay spacing criteria is preferred. This requires saving of the past history of traffic locations. Since TCAS senses traffic position relative to Own aircraft, it is necessary to incorporate Own navigational position to obtain a ground reference for the traffic. The history location corresponding to the desired time-delay interval then becomes the target location for Own aircraft. Displaying history dots at 4 second intervals was found to be very effective in allowing the trailing aircraft to follow the Lead during turns.

The ultimate use of TCAS in an enhanced combination with pictorial navigation information is closest to the Langley research scenario. It was demonstrated that self spacing could be utilized from cruise to the outer marker, but it required time-delay spacing criteria and extensive display enhancements. These included a plan-view display with map and ground-referenced traffic, assistance to capture the desired trail position, and a target history trail to follow during turns. It would be desireable to put spacing guidance on primary displays. The flight director could be used for path guidance with a fast-slow indicator for spacing. A Head Up Display could be used for final approach spacing and wake vortex avoidance inside the outer marker. A first cut at a speed-command algorithm, which compensates for actual groundspeed of the target and desired approach speed of Own aircraft has been tested with time errors less than half a second over the threshold. Without speed control on final (inside the outer marker to the threshold), there will be large interarrival time errors due to pilot variations in approach speed.

Knowledge of traffic identification was always assumed in the Langley scenarios. During departure operations pilots had a difficult time finding targets called by Air Traffic Control even with flight ID tags on the traffic. There were typically 4 to 5 targets on the display at the time. Plan-view traffic displays are apparently not intuitive to the pilot, and recognition of specific targets is not a simple task. Training the pilot to use the new displays properly takes considerable time. During the simulation tests pilot variations were always a significant factor in the results. Operational evaluation of pilot performance will be essential. Successful use of TCAS will require consistent performance by the below average pilot whereas the simulation studies have traditionally attracted the above average, highly motivated pilots.

PREVIOUS STUDIES - In-Trail Following via CDTI
Operational Cockpit Simulator Research - NASA Langley

- Current minimum level TCAS display not evaluated

- Display used was electronic Nav display on Wx radar location

  - Track up with traffic displayed relative to ground features

  - Traffic update every 1 - 4 sec

- Findings - Current TCAS display format

  - Distance spacing of limited use for descending decelerating approach

  - Que indicating Lead deceleration and ground speed more important than display size or sensor accuracy

  - High traffic update rate important

- Findings - Minimum TCAS enhancements

  - Simplest requirement - display relative velocity for improved spacing

  - Use Constant Time Delay - tie TCAS to Navigation with stored history

PREVIOUS RESEARCH - NASA Langley (CONT')

- Findings - Ultimate Use of TCAS Information

  - Comes closest to Langley research efforts

  - Requires extensive display enhancements

    - Planview with map and ground reference

    - Acceleration/deceleration required with Lead history trail

    - Spacing guidance on primary displays and flight director

    - HUD for final approach spacing and wake vortex avoidance

  - Concluded that with ATC automation aids and HUD, TCAS-derived approach speeds can reduce interarrival error to very small value

- Findings - General

  - Even with i.d. tags, pilots had trouble finding ATC designated targets

  - Operational evaluation of pilot performance essential; during simulations, pilot variation always a significant factor

  - Successful use of TCAS depends on consistent performance by below average pilot. Simulation studies usually have above average, highly motivated pilots.

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CDTI Cockpit Simulation Studies - MIT - 1970-1977 [17]

A sequence of research projects was undertaken by M.I.T. during the 1970-1977 period to evaluate the potential usefulness of an integrated display of traffic, map, and weather information in an aircraft cockpit and to ascertain the effects that the availability of such information would have on air traffic control procedures and performances. Real-time simulation tests involving a total of about 100 professional pilots indicated that the airborne traffic situation display (ATSD) would be a valuable aid in conflict detection and resolution, conforming to airspace structures, precise spacing in trail, merging, sequencing, monitoring runway occupancy, executing backup procedures after an ATC failure, monitoring the adjacent approach when two closely-spaced parallel runways are operating independently, and taxiing on the airport surface in reduced visibility. A simulation study of a terminal area metering and spacing system in which computer-generated commands were transmitted directly to the pilots showed that the introduction of the ATSD eliminated all violations of spacing minimums and cut the dispersion of arrival times at the runway threshold in half. When the ATC-generated metering and spacing schedule was made available to the pilots and their flight instruments were modified to assist them in executing a 4D RNAV approach corresponding to the schedule, the dispersion of arrival time errors at the runway threshold was reduced to less than three seconds.

An alternative ATC system configuration based upon a greater degree of pilot participation in the ATC process (distributed management) was suggested for the post-1985 period. In this concept, the key element was a modularly expandable avionics device that can provide navigation, collision avoidance, and communication functions, the full ATSD capability being its most sophisticated embodiment. A cost-benefit analysis indicated significant advantages for the proposed system in terms of greater capacities (reduced delays), greater safety, improved aircraft operational efficiency, and reduced ATC capital and operating costs. The work did not consider dynamic traffic response (Only one piloted simulator was used.) or controller interaction (No professional controllers were involved.).

PREVIOUS STUDIES - In-Trail Following via CDTI
Operational Cockpit Simulator Research - MIT FTL

- Research Projects Evaluated Usefulness of Integrated Display of Traffic, Map, and Weather Information in Cockpit.

- Projects Ascertained Effects of Such Information on Air Traffic Control Procedures and Performance.

- Real-time Simulation Tests Involved About 100 Professional Pilots Using Airborne Traffic Situation Display (ATSD)

- Tests Indicated that ATSD Valuable Aid in Conflict Detection and Resolution, Conforming to Airspace Structures, Precise Spacing in Trail, Merging, Sequencing, Monitoring Runway Occupancy, Executing Backup Procedures to ATC Failure, Monitoring Adjacent Parallel Approach, and Airport Surface Taxiing in Reduced Visibility.

- Introduction of ATSD Eliminated All Violations of Spacing Minimums and Cut Runway Arrival Time Dispersions in Half.

CDTI Research Emphasizing Human Factors - NASA Ames

Several experiments were run at NASA Ames Research Center over a five-year period focusing on developing a knowledge base concerning the content and use of cockpit traffic displays. Elements of this interface that were emphasized were those that enhanced the understanding of the human factors involved [18,19].

The following objectives were addressed in this series of studies:

1. Measurement of pilot opinion concerning the information content and format of the CDTI display.

2. Determination of the pilot's performance via display interpretation while conducting particular CDTI application functions - mainly in-trail following tasks.

3. Measurement of the system efficiency gains (runway throughput) when the cockpit traffic displays are available and used for in-trail spacing;

4. Evaluation of pilot situation awareness of adjacent traffic via the CDTI

Two of the important findings of this work were:

1. The aircraft spacing behind a given Lead aircraft became excessive in the final stages of approach using the CDTI. This was because the pilot's attention shifted from following the Lead aircraft via the CDTI to setting up and landing his Own aircraft.

2. The flight crew workload during in-trail following tasks was significantly higher than when there was no in-trail following task.

PREVIOUS STUDIES - Traffic Display Research
Cockpit Simulator (Human Factors) - NASA Ames

Content and Use of Traffic Displays

- Measured Pilot Opinion of Information Content and Format
- Determined Pilot Performance in Display Interpretation
- Measured System Efficiency (Runway Throughput) with Cockpit Traffic Displays
- Evaluated Pilot Situation Awareness of Traffic
- Found Aircraft Spacing from Lead Became Excessive in Final Stages of Approach Using CDTI for In-Trail Following
- Found that In-trail Following Workload was Significantly Higher than for no Following Task

Summary of Relevant Research, Development and Testing

Display of traffic information was found to be a valuable aid in conflict detection and resolution, airspace conformance, merging, sequencing and parallel runway approach monitoring. It has been demonstrated that a properly designed cockpit display of traffic information will permit flight crews to assist air traffic controllers in tightening the spacing tolerances between adjacent aircraft to increase airspace capacity and reduce delays. With proper displays and onboard navigation it is possible to have adjacent aircraft landings spaced in time to a precision of about 5 sec one sigma. The TCAS II system which has been developed as a backup to the primary Air Traffic Control system can provide the necessary surveillance in most cases provided that aircraft are equipped with diversity antennas.

The Phase II effort does not have to prove the utility of traffic information in the cockpit. That has already been demonstrated. Phase II should focus on improving the display of TCAS surveillance data to the pilot, developing the operational procedures for both pilots and controllers, modifying the separation standards, and flight tests. Other items of relevance include:

1. The TCAS traffic display will need modification to expand the traffic volume and to provide suitable information for in-trail spacing. The display will have to show appropriate range marks and range rate information in order that the pilot can perform the task.

2. Pilots will not use the spacing information inside the outer marker unless it is in their primary scan. There will be an increase in pilot workload, but it is considered acceptable.

3. Target identity will have to be established operationally as TCAS does not provide aircraft identity. Previous research has always assumed identity was available.

4. The normal resolution advisory logic will give false alarms during closely spaced approaches. New resolution logic will need to be developed if the TCAS is to provide threat protection against blunders during parallel approaches. This requirement could be waived in favor of the gound-based parallel runway monitor. TCAS II bearing accuracy of 8 deg one sigma limits the resolution of approach blunders to climb maneuvers only.

5. The TCAS traffic alert improves daylight visual acquisition by a factor of nine over unalerted search.

IV. CURRENT TCAS II DESIGN ADEQUACY

An important task of the Phase I effort was to critique the current TCAS II design to see if it is adequate for the CDTI applications presented in Section II. The Technical Team (a) addressed the Section II questions that had been posed concerning safety, surveillance and tracking, display generation, and human factors, and (b) conducted the review of relevant TCAS and CDTI research and development summarized in Section III. In addition, the team conducted the following activities:

1. The TCAS II MOPS specifications, TCAS Limited Installation Program (LIP) results, Parallel Runway Monitor (PRM), Terminal ATC Automation (TATCA) ghosting concepts, and other related projects and reports were reviewed.

2. Visits were made to Rockwell Collins, and Bendix-King to review the TCAS II designs. At Bendix, team members observed operation of the TCAS II display in the Bendix aircraft during flight. This gave the team an assessment of the quality of the TCAS display of other aircraft and the utility of using the display for improving visual acquisition, departure separation, and in-trail following - three of the proposed CDTI applications.

3. Team members rode on the FAA B-727 aircraft during an FAA Technical Center test and demonstration of the Bendix PRM system at Raleigh-Durham airport. A hybrid TCAS II system, consisting of a Honeywell antenna system and a Bendix display, was in this aircraft. A Convair 580 flew as the Other aircraft on the right parallel runway approach to the airport; the B-727 flew the left runway approach. The C-580 made intentional blunders during each parallel approach to test the PRM system and to obtain qualitative reactions from controllers and pilots participating in the tests. The team members were able to monitor the relative position of the C-580 out of the B-727 window as well as to watch the associated TCAS symbology on the on-board display. This gave the team a first hand assessment of the utility of TCAS for providing the CDTI function for independent parallel approaches. In addition, nuisance and missed TCAS alarms were both observed on several of these flights.

4. A simplifed relative position and velocity estimation error analysis was conducted by assuming that TCAS range and bearing measurement processing uses an alpha-beta tracker formulation to produce estimates of the target (that is, the Other or Lead aircraft) Cartesian X-Y coordinates and their derivatives. The associated position and velocity errors were derived as functions of assumed range and bearing measurement errors. This analysis is outlined in Appendix A, and is summarized later in this section.

5. Considerable discussion and, in some cases, debate was conducted among the team members as to what the engineering needs were for realizing the CDTI applications. This was based upon the review summarized in Section III, the four previous steps, and the considerable experience of the team members on various aspects of the CDTI concepts.

Based on these steps, technical judgements were made on the appropriateness of each of the suggested CDTI applications and the adequacy of the current TCAS II design to fulfill the CDTI traffic sensor role for each application. Each application is discussed in turn, relative to this assessment.

Improve Visual Acquisition

This passive CDTI application seems to be a straightforward one that will not require any modifications to the present TCAS design. During the LIP program, pilots reported that the TCAS aided them in sighting other aircraft. The most benefit will be gained from this application during marginal VFR conditions when other aircraft are hard to see and may disappear in haze or clouds

from time to time. The TCAS serving as a traffic display will allow the flight crew to sight and to monitor the position of adjacent aircraft for more of the flight time allowing VFR rules to be in effect over these additional time periods. Thus, this application can improve both the safety of flight and the airspace capacity, because flight under visual flight rules is inherently more efficient than under instrument rules.

It is recommended that data be taken during the TCAS Transition Program (TTP) to verify that visual acquisition is improved by using the TCAS and that during marginal VFR conditions, these rules may be maintained longer if the aircraft are TCAS equipped. The operational procedures existing between controller and flight crew under marginal VFR conditions should be reviewed to see if TCAS presence has any impact.

CURRENT TCAS II DESIGN ADEQUACY

Decision Process

- TCAS MOPS, LIP Program results, and previous TCAS and CDTI research reports reviewed

- Visits made to Collins and Bendix to review TCAS II designs. Operation of TCAS display reviewed in Bendix aircraft flight demonstration.

- FAATC flight test of PRM at Raleigh-Durham observed in B727 aircraft with operating TCAS

- Display observations during departure, final approach, and parallel approach scenarios provided first hand assessment of display quality and ability to support proposed CDTI applications

- Display error analyses conducted to examine effect of potential bearing error on departure and final approach spacing and parallel/converging approaches.

- Judgments made as to appropriateness of application based on limited data; unanswered technical and operational issues require further work

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Departure Separation Reduction

Based upon observing the relatively stable nature of the Other aircraft symbology on the TCAS screen and the clarity which the pilot can discern his Own position relative to another aircraft that is departing before Own, it was the Team concensus that the current TCAS system is capable of supporting departure separation reduction during IMC. The range and bearing accuracies of the TCAS surveillance system support observing 2 - 2.5 nmi separations and 15° departure course divergences. Also, the relative kinematics that are existing during consecutive departures favor this application. The Lead aircraft is accelerating and pulling away from Own during most of the departure sequence. The TCAS-CDTI display gives Own pilot the assurance that the separation is adequate, much like what he observes visually during VMC operations.

While this CDTI application looks favorable with the current TCAS, there are some caveats that must be made to this general conclusion and certain operation details that must be addressed. These are:

1. During departure, the Lead aircraft must be continuously visible on the CDTI display. This probably requires that the Lead aircraft also be TCAS equipped with diversity (dual above and below) antennae so that surveillance is not lost as the Lead rotates and shields the underside antenna.

2. Multipath anomolies will occur at many airports and in the presence of heavy aircraft ground traffic. It must be determined to what extent the presence of multipath adversely affects this application. Certain airports, runways, or traffic conditions may produce multipath problems such that this application can not be locally used. For these cases, procedures must be devised that allow use of departure separation reduction via CDTI only as is safe and as observing the Lead aircraft is unambiguous under the local conditions.

3. A means of identifying which aircraft is the Lead in a multiple aircraft environment (such as during dual departures) must be established. Several means exist including (a) logical deduction by Own's crew based upon the observed altitude time history and relative position of the candidate Lead, (b) providing an identity tag for the Lead on the display, or (c) marking the Lead aircraft with a separate color or symbol on the display.

4. Procedures need to be developed for both the flight crew and the departure controllers for this CDTI application. These procedures need to take into account that the commercial transport fleet will be only partially TCAS equipped for some time.

5. The increase in flight crew and controller workload that this application will cause during the departure period needs to be examined. It must be established that the increased runway capacity that reduced departure separation produces is well worth the extra work involved, and that this workload increase does not compromise flight safety.

The questions of whether this application would require that the display have adjustable range rings and relative velocity computation and display were addressed. These two enhancements are required for the last three applications, but it was the team consensus that they would not be required for departure separation. It was the team's belief that the fixed range rings set at 2.0 or 3.0 nmi will be adequate display information for judging the magnitude and monitoring the departure separation. Also, because Own aircraft's crew will not be attempting to close and maintain a certain separtion distance, relative velocity information will not be needed.

CURRENT TCAS II DESIGN ADEQUACY

Departure Separation Reduction

- TCAS II capable of supporting departure separation reduction.

  - Range and bearing accuracies support observing 2 - 2.5 nmi separations and 15 deg course divergence

  - Relative kinematics favorable; Lead is accelerating and pulling away

- However

  - Lead aircraft surveillance must be continuously available

  - Multipath anomolies will occur and must be delt with procedurally

  - ATC clearance procedures need to he established

  - Positive identification of Lead aircraft in multiple aircraft environment must be established

  - Cockpit procedures must be established

  - Pilot workload and human factors need to be studied

In-Trail Following

The current TCAS surveillance system and display has the potential of supporting in-trail spacing reduction and station-keeping in IMC. However, this flight procedure can only be applied during straight, constant speed portions of the nominal approach flight profile. By using the TCAS constant range rings to implement a Constant Distance separation criteria, large spacing errors during constant speed portions can be removed. There are many runway approaches where long final approach legs have large portions using 170 kt speeds (e.g., SFO Rwy 28L and R, BOS Rwy 4L and R). It is during these legs that the flight crew could use this application to assist the controller in lowering the inter-aircraft arrival error and thereby increasing the runway throughput.

To realize this potential benefit, the TCAS-CDTI display will require enhancement. The minimum separations required between consecutive aircraft prior to reaching the Final Approach Fix must be set based upon (a) the minimum final separations that are allowed and desirable (aircraft type and runway dependent) prior to landing, (b) the nominal speed used for the segment of flight being considered, and (c) the prevailing winds. Because the aircraft approach speed is decreased by controller advisories in a stepwise fashion, the allowable separations also decrease in this same manner. Thus, flight crews using the CDTI to close to some specified distance need to be able to set this distance on their display. This requires having adjustable range rings, a special range marker, or range spacing interval ("tick") marks on the display. Also, based upon the results of in-trail following experiments conducted at NASA Langley Research Center, to provide for the pilot to successfully close the spacing gap, it will be necessary for the CDTI to have some type of relative range rate indication to give a visual measure of instantaneous closing rate. Adjustable range rings and relative range rate display are not currently part of any TCAS mechanization. However, the information is available within the current software, so these requirements will be relatively straightforward to realize.

As discussed previously in Section III, the Constant Distance separation criterion is limited in application because it causes each consecutive aircraft in an approaching string to decelerate earlier in range-to-go to touchdown. This would produce an overall slowdown to approach which could result in unacceptable fuel penalties and operational problems. To mechanize an alternate separation criterion (either Constant Time Delay or Acceleration Cue criterion) that will allow tight control during both constant speed and deceleration portions of final approach will require more sophisticated time-based displays and flight guidance using primary flight display mechanization.

Additional issues that need to be addressed for this application include:

1. Depending upon the prevailing conditions, the desired minimum spacing for a given phase of the approach path will vary. A method must be devised to allow the controller to compute this spacing and communicate it to the CDTI-equipped aircraft flight crew.

2. In addition to setting the spacing desired, the procedures used by the flight crew and the approach controller when in-trail spacing is in effect, must be established. This application implies that the flight crew accepts in-trail separation responsibility, and the controller monitors this separation, much like during visual flight rules. The procedure for transition of the responsibility back to the controller during waveoff because of missed approach, runway obstacles, etc. must also be established.

3. Also, as terminal ATC automation aids come on-line to provide controllers with the means to tighten the in-trail separation from the ground, there must be a coordination with the airborne CDTI capability. It is not known at this point, whether airborne in-trail spacing control and ground-based automation aids to tighten final approach spacing will be complementary or redundant.

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4. There will be additional mechanization cost to provide the CDTI display enhancements to realize in-trail separation control capability. Also, there will be increased workload required on the part of the flight crew to control spacing via CDTI. Workload impact on the controllers may decrease, but this is not a certainty. These cost impacts have to be weighed against the potential increase in runway throughput that in-trail spacing control via CDTI may provide.

5. Special flight crew and controller training may be required to enable successful use of this CDTI application. If so, then there must also be a procedural way to determine, on the part of the controller, if the approaching flight crews are qualified to use on-board in-trail following procedures.

CURRENT TCAS II DESIGN ADEQUACY

In-Trail Following

- Current TCAS surveillance has the potential for supporting IMC in-trail spacing reduction during straight and relatively constant speed flight phases including along final approach.

- Minimum display requirements are range spacing interval marks, adjustable range marker, and relative velocity indication of Lead aircraft; these requirements are not available in all TCAS systems.

- In-trail spacing during decelerating final approach will require more sophisticated time-based spacing guidance provided on primary flight displays.

- Additional Issues

  - Display of spacing requirements to support basic decelerating descending approach need to be established

  - Ground/air coordination including waveoff procedures need to be researched to assess how to close spacing gap and to re-open in case of missed approach

  - The tradeoffs between increased runway capacity, controller/flight crew workload, and cost with increased TCAS surveillance and display sophistication need to be made

## Parallel and Converging Approaches - Dependent Case

For the dependent approaches, the controller's objective is the same for both parallel and converging runways. That is, a certain minimum range must be maintained between aircraft on the two approaches. This slant range, referred to as stagger, must currently be held to at least 2.0 nmi. for parallel approaches. For converging approaches, the distance between Own and the projection of the Other aircraft onto Own's approach must be held to at least 2.0 nmi. It is the controller's job to position the alternate aircraft so that their stagger ranges are as close as possible to this desired separation. Again, tightness in control of this separation increases runway capacity. Research is underway to determine if this minimum distance can be lowered and if the minimum separation between parallel runways in IMC can be reduced from the current minimum 2500 ft.

CDTI can potentially be used to allow the flight crew to assist the approach controllers in lowering the spacing errors that exist today in achieving the desired stagger ranges. In this sense, the CDTI provides a means for increasing runway capacity. In addition, by using the CDTI to detect blunders on the part of the Other aircraft, safety of flight is increased.

For the CDTI to be used to reduce and control stagger range or Own aircraft-Other aircraft projection range, the same issues as in-trail following just discussed apply. Additional issues that must be addressed include:

1. For maintaining in-trail and lateral separations for various parallel and converging geometries, the effect of the TCAS surveillance and tracking errors must be re-assessed.

2. Surveillance reliability must be established. Several times during the team's observation of the Raleigh-Durham parallel approaches, the TCAS image of the Other aircraft dropped off the screen. The Other aircraft was not TCAS equipped so it did not have a top antenna; when the Other aircraft turned toward Own's path, the lower antenna was shielded. This may imply that for this application, both aircraft involved must be equipped with diversity antennae.

3. The CDTI display requirements to allow dependent approaches in IMC need to be resolved. Questions of whether the Other aircraft's path needs to be computed, how the stagger distance should be shown, and how to project Other's position onto Own's path for the converging case will require investigation.

4. The questions of flight crew-controller procedures, workload issues, and training requirements have to be addressed as with the other applications.

CURRENT TCAS II DESIGN ADEQUACY

**Parallel and Converging Approaches
Dependent Case**
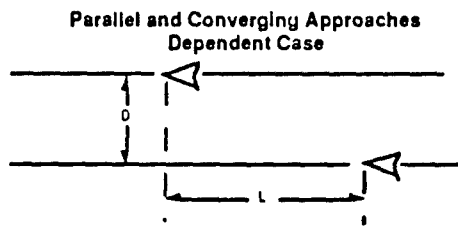
- Potential payoff is possible in reducing lateral (D) and longitudinal (L) separations

- To reduce longitudinal separation, same issues as in-trail following must be addressed

- Additional issues:

  - Safe minimum D and L combinations for the current TCAS '; surveillance accuracy need to be established

  - Surveillance reliability needs investigation

  - Flight crew and controller procedures and display requirements need to be resolved

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Parallel and Converging Approaches - Independent Case

The CDTI could be used for two different functions for parallel independent approaches: (a) to provide the mechanism to control in-trail spacing so that side-by-side flight is maintained (that is, to drive the longitudinal spacing L to zero); and (b) to provide lateral protection against a blunder on the part of the Other aircraft.

The first function - longitudinal spacing control - uses the CDTI to increase runway capacity. Maintaining side-by-side operation decreases the amount of spacing that must be allowed for departing aircraft on crossing runways. To reduce longitudinal separation, the same issues as in-trail following need to be addressed. Some guidance generation will be required to allow maintaining the desired spacing when the Other aircraft is decelerating.

For the second function - lateral blunder protection - the current TCAS threat logic is not designed to support lateral separation for side-by-side operation as is ideal for independent parallel approaches. Thus, as a minimum, this logic would need to be modified to include an independent parallel approach mode. Other issues include:

1. For providing an airborne alternative to the Parallel Runway Monitor (if this is desirable), a significant amount of research will be required. This includes conducting mathematical and simulation analyses of the relative dynamics of aircraft flying abreast with one aircraft blundering into the path of the other. Factors needed are the effects of flight crew reaction times, TCAS surveillance and tracking errors, and the consequential false and missed alarm probabilities.

2. The display requirements may include depicting the nominal ground tracks of both aircraft in addition to some type of "no transgression zone" between them.

3. The threat logic must be expanded to include provision for converging approaches and the relative dynamics involved.

4. Flight crew and controller procedures, workload assessment, and establishing training requirements will be required for this application as with the others.

5. Finally, to realize this application, will require increased costs for the CDTI system as well as additional controller and flight crew training. These have to be balanced against the potential benefits of increased runway throughput or the alternative of using the PRM.

CURRENT TCAS II DESIGN ADEQUACY

Parallel and Converging Approaches
Independent Case

- Required safety cannot be provided for side-by-side operations with the current TCAS II threat logic. CDTI has the potential to reduce the separation gap (L) to abreast operation for throughput efficiency.

- To close longitudinal separation, the same issues as in-trail following need to be addressed.

- To reduce lateral separation, several additional issues need to be addressed:

  - Mathematical and simulation analyses of relative dynamics (including human reaction time effects), surveillance accuracy, and false alarm and missed alarm probabilities

  - Revision of threat logic for parallel or converging dynamics

  - Modifications of display format to show ground reference and intended tracks

  - Flight crew and controller procedures, workload studies, and training requirements

TCAS Traffic Sensor and Tracker Adequacy

Previous research has shown that successful in-trail spacing requires the display of along-track relative velocity. The necessary accuracy is expected to be near five kt one sigma. On landing approach, conflict resolution in the vertical plane will probably be limited to climb maneuvers only because of the potential for conflict with the Ground Proximity Warning System. In order to use horizontal resolution it is necessary to predict the horizontal miss distance which depends on the relative velocity of the threat. The accuracy of the miss distance estimate and the horizontal resolution advisory depend on the velocity estimation accuracy.

To begin to make this accuracy assessment, a simplified Other aircraft velocity estimation error analysis was conducted which is summarized here. More detail is found in Appendix A.

The error sources that will affect the TCAS display output include

1. The range and bearing measurement errors provided by the TCAS surveillance system;

2. The absense of roll and pitch attitude compensation of Own aircraft in the filter mechanization. Ideally, the TCAS Cartesian computation frame is tied to a locally level inertial reference frame. Because the range and bearing measurements get transformed to Cartesian X-Y components, without compensation, these components will be in error if the aircraft is pitched or rolled away from a straight and level flight attitude.

3. The filter mechanization used by TCAS is based upon the assumption that all aircraft being tracked and Own aircraft are flying straight, constant speed segments. Thus, any accelerations of Own or Other aircraft will produce tracking errors.

In the following, only the effects of range and bearing errors are considered.

The signal processing used by the TCAS is known as an alpha-beta filter. This is depicted by the block diagram and discrete state equations on the opposite page. The range and bearing values r and β are subject to measurement errors δr and $\delta \beta$ to produce the measurements r_m and β_m. These measurements are transformed to Cartesian values x_m and y_m. These transformed measurements are passed through the filter equations to produce estimates of position and velocity of the Other aircraft. These estimates are designated by the "^" over the values. Velocity components of x and y are designated by the dot "·" over the values. For the particular analysis discussed here, the fixed gains α and β were set to 0.18 and 0.0091, respectively. It was assumed that measurements and estimate updates are made every time step Δ equal to 1.0 sec.

The steady state error statistics of the estimated position and velocity components that are the outputs of the alpha-beta filter can be shown to be related to the input statistics by the expressions shown. That is, the standard deviation of the estimated position component x will be 0.34 times the size of the standard deviation of the measured position component x_m's error. The standard deviation of the estimated velocity component in the x direction will be 0.016 times x_m's error.

These error characteristics can be transformed to determine how they would affect the position and velocity estimates for different positions of the Other aircraft. In the second diagram, three different geometries are depicted for the CDTI being used for in-trail following, stagger control for dependent parallel approach, and side-by-side control for independent parallel approach.

If the range error standard deviation is 200 ft and the bearing standard deviation is 8° (both conservative values), the resulting speed error components are as indicated below each sketch. The first line designated σ_v gives the total speed error in kt. The next line is the speed error

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Simplified Velocity Estimation Error Analysis

- Error Sources
  - Range and bearing measurement errors
  - Own attitude
  - Own and lead accelerations

- Simple Analysis Model
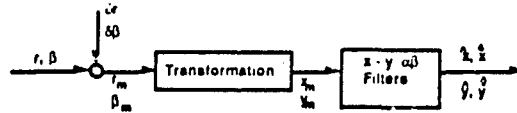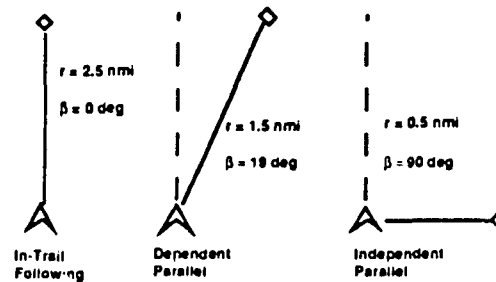

- Alpha-Beta Filter

$$\begin{bmatrix} \hat{x} \\ \dot{\hat{x}} \end{bmatrix}_{n+1} = \begin{bmatrix} 1 & \Delta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{x} \\ \dot{\hat{x}} \end{bmatrix}_n + \begin{bmatrix} \alpha \\ \beta/\Delta \end{bmatrix} \left[x_m - (\hat{x} + \dot{\hat{x}}\Delta)_n \right]$$

- Estimation Error (Typical) for $\alpha = 0.18$; $\beta = 0.0091$; $\Delta = 1$ sec

$$(\sigma_{\hat{x}})^2 = (0.34\,\sigma_x)^2 \; ; \;\; (\sigma_{\dot{\hat{x}}})^2 = (0.016\,\sigma_x)^2$$

Simplified Velocity Estimation Error Analysis
(Cont')

- Examples

In-Trail Following	Dependent Parallel	Independent Parallel
$r = 2.5$ nmi	$r = 1.5$ nmi	$r = 0.5$ nmi
$\beta = 0$ deg	$\beta = 19$ deg	$\beta = 90$ deg

For $\sigma_r = 200$ ft and $\sigma_\beta = 8$ deg, speed component errors are

$\sigma_v = 20.2$ kt	$\sigma_v = 12.2$ kt	$\sigma_v = 4.5$ kt
$\sigma_{\dot{r}} = 1.9$ kt	$\sigma_{\dot{r}} = 1.9$ kt	$\sigma_{\dot{r}} = 1.9$ kt
$\sigma_{r\dot{\beta}} = 20.1$ kt	$\sigma_{r\dot{\beta}} = 12.1$ kt	$\sigma_{r\dot{\beta}} = 4.0$ kt

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component along the range line (i.e., the range rate error). It is a constant 1.9 kt. The third line gives the cross range error which increases linearly proportional to range. It varies from 4.0 kt for 0.5 nmi range (parallel side-by-side) to 20.1 kt for 2.5 nmi range (as for close in-trail following).

From these calculations it appears that the existing TCAS II accuracy is adequate for in-trail spacing. However, the existing TCAS II bearing accuracy of 8 deg one sigma is inadequate to support horizontal resolution of approach blunders.

V. NEED FOR FURTHER WORK

This section summarizes the Technical Team's consensus position on work that remains to be accomplished in order that the five CDTI applications can be fully mechanized and made operational. First, general conclusions are made that apply to all applications and to the general task of developing future fleetwide cockpit traffic displays to enable flight crew aid in the traffic management process. This is followed by a summary of the basic technical requirements that must be addressed for each application. Then, the specific required features, or TCAS II enhancements that are needed for the applications are presented. Finally, some of the detailed requirements for further engineering development are summarized.

General Conclusions

As stated before, the passive application of using the TCAS display for improving visual acquisition can be advanced by using the TTP data collection and analysis process to quantify the benefits and to modify, as required, any controller-flight crew procedures that are applicable during marginal VFR conditions when this application will provide the most payoff.

All active CDTI applications require TCAS system enhancements to some degree. The departure clearance application requires the least amount of modification, although it may be necessary to provide for adjustable range rings and possibly a relative velocity indication. On the other end of the spectrum, providing for use of the TCAS-CDTI to enable independent parallel approaches, if this is warrented, will require major system analysis and design modification. In conclusion, these enhancements will require further technical analysis, design and testing of an enhanced TCAS system.

This study was limited to considering to what extent the TCAS II design could be used for CDTI applications as it currently is designed or with modest enhancements. However, it is the strong opinion of the Technical Team members that in the long run, the TCAS function of collision avoidance should be isolated by design from the CDTI applications. This would be so that the elaborate filtering and threat logic certification that has already been completed for TCAS II would not have to be repeated because of logic changes to mechanize CDTI.

The general desire to implement CDTI applications, both for the terminal area considered in this study and for other phases of flight, requires the future development of a new airborne "ATC module" rather than extension of the current TCAS. This module would have the following features:

1. It would use direct input from the TCAS traffic sensor. It would also obtain input from the FMS or RNAV systems so that the display coordinate frame would be tied to the earth for map generation and other fixed symbology. It also would be tied directly to ATC computers via data link for future air-ground cooperative ATC developments. There may also be some advantage to have direct data link with adjacent aircraft.

2. The function of this module would be to supplement the primary TCAS function with parallel enhancements. That is, TCAS would continue to protect the aircraft from mid-air collision. CDTI would enable more efficient use of the airspace for capacity improvements.

3. The output of the CDTI-ATC module would be on a primary map display, heads up display, or flight director. In other words, for tight spacing control, especially as the aircraft enters final approach, the CDTI information has to be in the pilot's primary field of view.

4. The module would provide for direct dialog between airborne and ground ATC computers.

CDTI applications should not be limited to the terminal area. Other flight phases (e.g., oceanic spacing) may have greater economic payoff. Thus, it is recommended that this study be expanded to consider these other applications.

NEED FOR FURTHER WORK
General Conclusions

1. All active CDTI applications require TCAS system enhancements to some degree.

2. The development of TCAS enhancements and establishment of active CDTI application system requirements and benefits require further technical analysis and testing

3. Passive application - Improve Visual Acquisition - can be advanced with TTP data collection and analysis only.

4. The general desire to implement CDTI applications to improve ATC efficiency requires development of a new airborne "ATC module".

   - Use input from TCAS sensor, FMS, RNAV and data link
   - Supplement TCAS threat logic with parallel enhancements
   - Output to primary map display, HUD, or flight director
   - Interact with ground ATC

5. CDTI applications should not be limited to terminal area; other flight phases (e.g., oceanic spacing) may have greater payoff.

Basis Requirements - All Applications

There are eight basic requirements that must be addressed for each of the active CDTI applications. These are:

1. The impact on flight safety of using the TCAS for CDTI must be addressed. It must be positively established that using the CDTI application to increase airspace capacity will not adversely affect the basic safety of flight.

2. Each of the CDTI applications is based on the assumption that the TCAS traffic sensor is a realiable surveillance system and that the position of the adjacent traffic is continuously available. The degree of surveillance reliability must be established, and the effect on flight safety and operational conduct if the traffic sensor is lost, even temporarily, must be considered. Operational procedures must be designed with this possibility in mind. Also, it must be shown that positive identification of the Other aircraft can always be readily established and maintained by glancing at the display.

3. Operational testing of each CDTI application must be conducted to include the effects of site specific aspects. These include the possibility of increased multipath errors in cluttered airports and the effects of variations in local nominal approach patterns.

4. Flight crew and controller procedures need to be developed for each application. The associated Airman's Information Manual and Air Traffic Controllers' Handbook must reflect these new procedures. These procedures must include provision for aircraft that are not TCAS equipped or that have different display capability.

5. It must be established that flight crews and controllers understand and approve the reasons for implementing the CDTI applications and associated new procedures, that they accept these changes in terms of possible increased workload, and that the increased workload is acceptable in terms of flight crew performance.

6. Given that implementing CDTI will increase airline equipment costs for the enhancements and additional training involved, and that CDTI applications will increase the flight crew workload, these costs must be compared to the potential capacity benefit gains to determine that the result is favorable and that further development work is warrented.

7. Flight crew and controller training requirements must be established to allow specific use of each of the CDTI applications.

8. Finally, the Federal Aviation Regulations must be modified to encompass the CDTI concepts. Flight standards and equipment certification processes will have to include provision for the CDTI.

NEED FOR FURTHER WORK (CONT')

BASIC REQUIREMENTS - ALL APPLICATIONS

- Safety impact must be evaluated
- Surveillance reliability and positive identification must be established
- Operational testing must be conducted including effects of site specific aspects such as increased multipath and variations in nominal approach patterns
- Flight crew and controller procedures need to be developed
- Flight crew and controller acceptance of procedures in terms of impact on safety and increased workload must be established
- Increased workload must be assessed with respect to anticipated benefits
- Crew and controller training requirements will be required
- Regulations must be modified to encompass the applications

Necessary TCAS Enhancements

The TCAS surveillance system volume of airspace coverage is limited depending upon the flight altitude of Own aircraft. This is to minimize display clutter from aircraft which do not present a potential threat and to prevent unwarrented alarms from adjacent aircraft in tight patterns near the airport. This surveillance volume will have to be adjusted to allow for mechanization of the active CDTI applications that are all to be mechanized within the close-in terminal airspace.

Each of the applications considered here requires the flight crew to judge accurately the range to the Other aircraft. This requires that the range rings and range scale be made available on the TCAS display to facilitate this judgement. It is desirable that the range rings be adjustable so that they can be set exactly as required by the separations used for each application.

Beyond these two general enhancements, each of the CDTI applications requires specific modifications to the current TCAS design. These requirements are summarized in the chart.

A diversity antenna is required on the Other aircraft (i.e., Other must also be TCAS equipped) to prevent shielding and loss of signal during departure separation control and lateral separation monitoring for independent parallel approaches.

Relative velocity indication is required, as a minimum, to allow closing in and maintaining a fixed separation with only range rings (Constant Distance criterion). This is definitely required for in-trail following, and for dependent and independent parallel runway approaches. There might be a need for this capability for departure separation control, although this wil' have to be established during the subsequent investigation.

The converging runway application will require tracking of aircraft from a considerable distance. The increased range increases the Other aircraft position uncertainty because of the bearing measurement error. Thus, this application may need improved bearing measurement available with TCAS III. Likewise, to provide sufficient blunder protection for the independent parallel approach case, enhanced bearing accuracy may be required.

To use the TCAS for spacing control for converging runway approaches will require that Own's crew can discern where the Other aircraft is relative to the Other's path and its projection on Own's path. This will require that the display include ground reference information available from the navigation system. Ground reference would also be useful for the independent parallel runway approach application.

For pilot efficiency and workload reduction, it is best that the CDTI information be in his primary scan. If the in-trail following is to be extended to spacing control inside the Final Approach Fix or Outer Marker, placing the CDTI display in the primary scan is an absolute necessity.

For the initial CDTI applications, the longitudinal separation control provided by using range rings and relative velocity will be relatively crude. That is, this capability will only allow removal of large spacing gaps during phases of constant speed flight. This separation criterion will not support spacing in the time domain which is necessary for tight control during the approach that includes periodic decelerations to new speeds by the Lead aircraft. For the independent parallel approach application, the objective will be for Own to close the gap so that Own is positioned parallel and abreast of the Other aircraft during the approach. This will require some additional along-track guidance information on the CDTI display. In addition, for spacing control inside the Outer Marker where there will be the conflicting objective of setting up and maintaining final approach and landing speeds, the pilot will need along-track guidance to resolve this conflict.

TCAS Enhancements Necessary to Support the Active Applications

- All applications require:
  - Adequate altitude volume
  - Range rings at desired separation plus range scale

- Application specific requirements:

Required Feature

Application	Diversity Antenna	Relative Velocity Indication	Enhanced Bearing Accuracy	Ground Reference Depiction	Display In Primary Scan	Along-track Guidance	Modified CAS Logic
Departure Separation	●	●					
In-trail Following		●					
Dependent Parallel Rwys		●					
Independent Parallel Rwys	●	●	●		●		●
Converging Runways			●	●			●
Spacing Inside OM		●			●	●	

If the TCAS-CDTI is to be extended to facilitate independent parallel approaches (that is, to serve as an airborne version of the PRM), then the collision avoidance logic has to be modified to provide blunder protection. Also, if converging runway approaches are to be facilitated via CDTI, then it might be necessary to project the position of the Other aircraft onto the path of Own [20]. The TCAS logic then would be modified to interact somehow with these "ghost" projections.

NEED FOR FURTHER WORK (CONT')

Research and Development Needed in Following Areas

- System Specification and Test Program Development

- Analysis and Fast Time Simulation

- ATC/Cockpit Simulator Real-Time Simulation Studies
  - Part-Task Simulations
  - Human Factors Analysis and Human-Computer Interface
  - Operational Feasibility Testing

- Flight Test and Demonstration
  - Dedicated Flight Tests
  - TCAS Transition Program (TTP) Data Collection and Analysis

Areas of Needed Research and Development

Four areas of endeavor are required to realize the mechanization of the CDTI applications. These are:

1. The CDTI system details must be specified, preliminary engineering design must be completed, and the test program plan must first be developed for each application. This initial activity would govern the course of the subsequent work.

2. After the design is established, backup analysis would be required to investigate cost-benefit tradeoffs, the effects of system errors and accuracy requirements. Monte Carlo and other fast time simulation techniques may be used to obtain certain measures of design requirements.

3. A large amount of the effort can be accomplished by use of cockpit simulation. This includes both part-task simulation to set the display characteristics, and full-mission simulation to develop procedures, measure workload effects, develop training requirements, and other human factors elements. The cockpit simulation phase would establish that the CDTI application is operationally feasible.

4. The final phase is flight test and application demonstration. Dedicated flight tests would be planned to follow the simulation phase to check simulation results and to include aspects that cannot be fully included in a cockpit simulator. In addition, advantage would be taken of the on-going TTP flight program where specific data would be requested for analysis to support the CDTI concepts and their mechanization.

NEED FOR FURTHER WORK (CONT')
Analysis and Fast Time Simulation

- Error analysis

  - Establish effects of range, bearing and other errors on Other aircraft position and velocity uncertainty

  - Determine necessary TCAS sensor accuracy requirements to support different application geometries

  - Establish TCAS logic false and missed alarm rates for different approach scenarios

- Algorithm development and testing

  - Simulate operation of new algorithms

    - Data filtering

    - RA threat logic for independent parallel operation

    - Enhanced display generation logic

- Analysis of cockpit simulator and flight tracking data

Analysis and Fast Time Simulation

As discussed in Section IV and Appendix A, an extensive error analysis needs to be made to determine the effects of range and bearing measurement errors, lack of aircraft attitude compensation, aircraft acceleration effects and other errors on the accuracy of the displayed positions and estimated velocities of Other tracked aircraft. This analysis would determine the necessary TCAS sensor accuracy that is required to support the different application flight geometries. Also, as a result of this study, the error statistics involving false and missed alarm rates of modified TCAS threat logic would be recomputed. These would have to be judged in terms of the minimum requirements for satisfying basic airborne safety needs.

Another aspect of the analysis would be to design, debug, and simulate the operation of the new algorithms that are required to enhance the TCAS display. This would include provision for such items as computing relative velocity, Own and Other positions with respect to a moving map display, provision for guidance commands, and ghost projections. New data filtering may be required. A new Resolution Advisory (RA) concept would have to be developed for the blunder protection aspect of parallel independent approaches. Enhanced display generation logic would also have to be checked.

Another analytical task would be the processing of both cockpit simulator and flight test data. This would include evaluation of the actual aircraft trajectories compared to those computed by the TCAS-CDTI system

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NEED FOR FURTHER WORK (CONT')
Cockpit Simulation Studies

- Develop display concepts and procedures in part-task workstation simulation

  - Real-time aircraft motion and display update
  - Linearized aircraft dynamics with joystick control
  - Simplified TCAS simulation
  - Highly modifiable display
  - Limited ATC interaction
  - Provides candidate displays and procedures for cockpit simulation

- Test full scenarios in piloted cockpit simulation

  - Full aircraft dynamics and realistic controls
  - High fidelity TCAS simulation
  - Live ATC interaction (pre-recorded traffic)
  - Provides displays and procedures for full system tests

- Analyze human factors in full system simulation

  - Full workload cockpit
  - ATC simulation (live pseudo-aircraft response)
  - Provides final validation prior to flight testing

Cockpit Simulation Studies

The display concepts and operating procedures can be developed in a part-task workstation type of cockpit simulation. This simulation would include real-time aircraft motion effects on the display and regular display updates. The aircraft motion would be based on linearized aircraft dynamics with joystick control. The TCAS simulation would be simplified so that it would facilitate ease of modifying different display features. The involvement of the air traffic controller in using this simulation would be minimal, and would only be necessary to check out the procedural flow.

The next step would be to go to a full scenario piloted cockpit simulation. This would include full aircraft dynamics and realistic controls. Here, a high fidelity TCAS simulation would be required for test purposes. Live ATC interaction would be required. The objective of this simulation would be to fine tune the displays and operating procedures in more realistic conditions. This would prepare the system for the subsequent full workload tests.

The final phase of cockpit simulation would be conducted in a full workload, full mission cockpit. The simulation would require full ATC simulation for high fidelity flight crew-controller interface study. This simulation would be used to investigate all human factors issues regarding use of the CDTI. It would also provide the final system validation prior to flight testing.

Human Factors Analysis

Human factors analysis is required for each CDTI application to ensure that pilots and controllers can perform the necessary elements to realize the potential of the application. For example, it must be established that average pilots can remove large in-trail spacing gaps in IMC by just using the range ring and relative velocity information from the CDTI. It must be determined when it is appropriate for the controller to request that the pilot use his CDTI to remove this spacing gap, and what monitoring is necessary on the part of the controller while the pilot conducts this maneuver. Part of this analysis would be to perfect the interactive procedures that are followed on part of controller and pilot throughout the application.

As mentioned before, human factors study is required to measure increased flight crew workload when using the CDTI. Safety impact assessments would also be made from these studies. These would be weighed against the increase in airspace and runway capacity expected from the CDTI applications.

Human factors analysis requires use of a full-mission environment. Testing would compare the performances obtained with current VFR use of outside visual information, current IFR operations conducted with advisories from ATC, and the new proposed CDTI procedures. Both pilot and controller performances and workload would be measured and assessed.

It is important to note the the experimental trials should only begin after the pilot and controller test subjects have been given ample time to learn the CDTI procedures.

NEED FOR FURTHER WORK (CONT')
Flight Tests - Dedicated

Phase II.a

- Objective: Evaluate TCAS-CDTI applications in controlled flight environment.

- Method: Determine operational variance using ground based "truth"

- Airborne Data: TCAS II measurements of Other aircraft range, altitude, bearing

- Ground Data: PRM recordings, ARTS sensor readings, precision tracker

- Processing : Compare TCAS measurements with best state estimate from ground information; establish statistical error model

Phase II.b

- Objective: Demonstrate capabilities of TCAS-CDTI with display upgrades

- Method: Integrate ground reference data and new symbology onto TCAS display

- Airborne Equippage: TCAS sensor, navigation and attitude inputs, modified symbol generator

- Ground data: PRM, ARTS, precision tracker

- Processing: Compare TCAS and ground state estimates; establish safety and gained capacity of applications using upgraded TCAS display

Dedicated Flight Tests

The flight tests dedicated for final evaluation and demonstration of the CDTI concepts would be structured into two phases. During the first phase, the objective would be to evaluate the TCAS-CDTI having minimal enhancements in a controlled flight environment. The relative dynamics between Own and Other aircraft for each application would be determined by comparing data taken from ground tracking systems (the "truth" model) and the TCAS systems on each aircraft. Ground tracking sources can include PRM facilities, normal ARTS tracking, and special precision tracking systems that can be brought to the facility. The data would be used to create a best estimate of both aircraft trajectories and to establish or verify the statistical error model for the TCAS-CDTI system.

During the second phase of flight testing, the more substantial enhancements to the TCAS display for the more complex applications would be investigated. This would include use of airborne navigation and attitude inputs as well as the substantially modified display modifications. Again, ground tracking would be compared with the airborne state estimates. The expected gains in airspace capacity would be verified as a result of the design enhancements. Also, the ability of the modified system to provide adequate blunder protection for parallel independent approaches would be verified and demonstrated to both flight crews and controllers.

NEED FOR FURTHER WORK (CONT')
Flight Tests - TCAS Transition Program (TTP)

- Develop specific requirements to collect data and verify feasibility of five applications

- Collect and analyze following qualitative data:

  1. Improve Visual Acquisition - flight crew ability to maintain visual contact in marginal VFR

  2. Departure Spacing

     - Displayed separations during VFR

     - Site-specific multipath problems

  3. In-trail Following

     - Assessment of constant speed final approach phases

     - Ability of pilot to close and maintain fixed spacing

  4. Parallel Approaches

     - Dependent - ability to close and maintain fixed stagger

     - Independent - ability to close to side-by-side approach

- Evaluate CDTI applications with respect to collected TTP data

TCAS Transition Program

In a sense, the TCAS Transition Program is a flight test period where data are being collected and analyzed to ensure that TCAS provides collision prevention, as expected. This test period offers a special opportunity to gain technical and operational insight into how well each of the suggested CDTI applications might work. Discussion was given earlier about how this program should be used to verify that visual acquisition could be improved via TCAS.

The TTP period is already underway, so it is imperative that the first step of Phase II of the CDTI-TCAS project be to affect the TTP project to obtain desired data. For the CDTI applicatio.is, the following data should be collected and analyzed from TTP flights:

1. Improve visual acquisition. Demonstrate the flight crew's ability to acquire and maintain visual contact with Other aircraft in marginal VFR conditions. Show that this allows the VFR rules to be used for longer periods of flight time which should improve overall terminal area capacity.

2. Departure spacing. Use displayed separations during VFR conditions to demonstrate that the TCAS display could be used to decrease times between consecutive departures during IMC. Investigate how site-specific multipath problems might affect this application.

3. In-trail following. Investigate during VFR approaches how Own aircraft pilot can use the TCAS with constant range rings to remove large spacing gaps during periods of constant speed flight by the Lead aircraft. Investigate how well the pilot can close and maintain fixed spacings with fixed range rings and no relative velocity information.

4. Parallel approaches. Under VFR conditions, investigate the pilot's ability to close and maintain a fixed stagger distance for dependent parallel approach geometries. For independent approach geometries, investigate the pilot's ability to close to a side-by-side approach condition.

VI. RECOMMENDATIONS

Based upon the review of previous TCAS development and CDTI research, an assessment of the adequacy of the current TCAS design, and an evaluation of the technical effort that remains to allow full realization of the CDTI applications, the Technical Team makes the following recommendations for the Phase II effort.

First, the general requirements that remain to be satisfied regarding TCAS II enhancements are summarized. Then, general recommendations are presented relative to the overall organization of a Phase II effort. This is followed by specific recommendations relative to the upcoming TCAS Transition Program and work to be done in areas of analysis and design, cockpit simulation, and flight test. This section concludes with a recommended Phase II schedule and budget.

Summary

Eight basic requirements were previously explained in Section V. These apply to all CDTI applications, and Phase II must be organized to ensure that each of these requirements are met for any CDTI application that is being seriously considered for mechanization. These basic requirements are:

1. Evaluate the application's impact on flight safety;

2. Establish that the TCAS surveillance system provides display input that is acceptably realiable and that positive identification of the Other aircraft can always be made;

3. Develop procedures for use of the CDTI when local anomalies such as multipath signal problems may be present; Consider variations in normal approach patterns;

4. Develop the procedures to be followed by the flight crews and the approach and departure controllers for use of the CDTI capability;

5. Establish the process whereby the flight crews and controllers understand and accept use of the CDTI procedures;

6. Assess the implementation costs and increased flight crew workload relative to the anticipated increase in airspace capacity expected from using the CDTI;

7. Develop training procedures for the flight crew and controller use of the CDTI; Establish minimum proficiency requirements to allow terminal area usage; and

8. Modify FARs and other documentation to encompass the CDTI applications.

With respect to the five suggested CDTI applications, certain enhancements will be necessary as are summarized in Section V. However, the current TCAS II design is sufficient to allow use for the passive application of improving visual acquisition of Other aircraft. The Technical Team also believes that the current design is sufficient to support the departure separation application, although there may be improved performance with addition of adjustable range rings and a relative velocity indication.

The in-trail spacing and dependent parallel approach applications will require the addition of adjustable range rings plus relative velocity computation and display. These are relatively simple display logic additions. However, with range ring only display of separation distances, these applications are limited to only allowing the removal of large spacing gaps during constant speed flight phases.

To implement the independent parallel and converging runway approach CDTI applications will require the addition of a significantly greated amount of TCAS display enhancement. The requirements include adjustable range rings, relative velocity indication, enhanced bearing accuracy, modified CAS protection logic, and along-track guidance. For these applications, investigations of (a) more accurate in-trail following capability with different spacing criterion, and (b) the use of a new ATC module are warrented.

SUMMARY

CDTI IMPLEMENTATION REQUIREMENTS

- Basic Requirements - All CDTI Applications

  - Evaluate safety impact

  - Establish surveillance reliability and positive identification

  - Develop procedures for operations with multipath anomalies and approach pattern variations

  - Develop flight crew and controller procedures

  - Establish flight crew/controller acceptance of procedures

  - Assess increased workload relative to anticipated benefits

  - Develop flight crew and controller training process

  - Modify regulations to encompass the CDTI applications

- TCAS Design Enhancement Requirements per Application

  - Visual Acquisition and Departure Separation - Current TCAS design sufficient

  - In-Trail Spacing and Dependent Parallel Approaches - Require adjustable range rings plus relative velocity; these are simple display logic additions; limited to removing large spacing gaps

  - Independent Parallel and Converging Runway Approaches - Require adjustable range rings, relative velocity, enhanced bearing accuracy, modified CAS protection logic, and along-track guidance. Include investigation of accurate in-trail following and airborne ATC module.

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General Recommendations

It is recommended that a Phase II effort be conducted to address the requirements to realize the potential of using TCAS II for terminal CDTI applications.

The FAA is currently supporting ground-based methods for enabling closely spaced independent parallel and dependent converging runway approaches [4, 20]. It is for this reason that the Technical Team recommends that Phase II be focused on the following four applications:

1. Improve visual acquisition;

2. Decrease departure separation in IMC;

3. Reduce in-trail spacing gaps during constant speed phases of approach; and

4. Control stagger separation to the minimum requirement during dependent parallel approaches.

However, the Technical Team recommends that other terminal area applications that have been investigated be continually pursued, even if only under limited funding. A limited set of complementary tasks should be planned and conducted to investigate:

1. Control of relative parallel position and provide blunder protection during independent parallel approaches;

2. Facilitate making converging approaches with appropriate relative spacing control during IMC; and

3. Develop a preliminary design of the ATC module that provides growth potential for more complex applications of CDTI including direct airborne-ground computer communications.

GENERAL RECOMMENDATIONS

- Pursue a Phase II Effort to Address the Requirements to Realize the Potential of Using TCAS II for Terminal CDTI Applications

- Focus on the Following Applications:
  - Improve Visual Acquisition
  - Departure Separation
  - In-Trail Spacing
  - Dependent Parallel Approaches

- Conduct a Limited Complementary Set of Tasks to Examine:
  - Independent Parallel Approaches
  - Converging Approaches
  - Airborne ATC Module

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Specific Recommendations

It is specifically recommended that Phase II be organized into four distinct types of activity with the accompanying tasks. These are:

1. TCAS Transition Program. Immediate advantage should be taken of this on-going project. The first task would be to develop requirements for data to be collected during the TTP flights, to collect and process these data, and to analyzed the results to answer specific questions concerning the use of the TCAS II system for CDTI applications. From this analysis, evaluate both the feasibility of using the TCAS II sensor and display for CDTI applications and the resultant impact on the safety of flight.

2. Analysis and Design. The first task should be to plan for the development of each CDTI application, including TCAS design enhancements, simulation, and flight tests. The error characteristics and elements of the system design need to be analyzed to determine the effects of estimated relative position and velocity error on the ability of the pilot to conduct the CTDI application. Error effects on basic conflict detection missed and false alarm rate need to be reassessed. The TCAS sensor accuracy requirements to support different approach and departure flight geometries need to be established. New filtering, threat logic, display generation, and ATC module software needs to be designed and tested.

3. Cockpit Simulation. The CDTI display concepts and operational procedures can first be designed and developed using a part-task (workstation) cockpit simulation. These display features and flight crew/controller interactions should then be tested in a piloted simulator with live ATC interaction. The final task would be to analyze the human factors aspects of the CDTI applications in a full mission cockpit simulator. Human factors aspects include investigation of safety aspects, procedures, crew workload, and training requirements.

4. Dedicated Flight Test. The first task should be to verify the previous results obtained from the TTP analysis, other off-line analysis and design, and the cockpit simulation results. The final task would be to demonstrate via flight to pilots and controllers the feasibility and recommended procedures for using CDTI to improve terminal airspace capacity and runway throughput.

SPECIFIC RECOMMENDATIONS
RELATIVE TO EACH CDTI APPLICATION

- TCAS Transition Program

  - Develop requirements for, collect, and analyze qualitative data
  - Evaluate feasibility and safety of CDTI applications from TTP data

- Analysis and Design

  - Determine error effects on position and velocity uncertainty, missed and false alarm rates
  - Determine TCAS sensor accuracy requirements to support different flight geometries
  - Design and test new filtering, threat logic, display generation, and ATC module concepts

- Cockpit Simulation

  - Develop display concepts and procedures in part-task (workstation) simulation
  - Test full scenarios in piloted simulator with live ATC interaction
  - Analyze human factors in full mission cockpit simulator - safety, procedures, workload, training

- Dedicated Flight Tests

  - Verify results of TTP, analysis, and cockpit simulation
  - Demonstrate to flight crews/controllers feasibility and recommended procedures of CDTI

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SPECIFIC RECOMMENDATIONS
CDTI SCHEDULE AND BUDGET

• Conduct a 33-month $2.0 million Phase II Engineering, Development, and Testing Phase in Parallel with TTP Program and TCAS Equipage Process

	Cost	Period - months
• TCAS Transitions Program -	$ 58.6K	1 - 12
• Analysis & Design		
• Analysis of errors, flight scenarios, etc. -	$105.8K	1 - 6
• Design of new filters, threat logic, ATC module -	$198.0K	7 - 12
• Cockpit Simulation		
• Develop concepts via part-task simulation -	$625.9K	1 - 12
• Test concepts & human factors via full		
work load simulation -	$571.6K	6 - 18
• Flight Tests		
• Verify TTP, analysis, and simulation results -	$245.5K	16 - 24
• Demonstrate feasibility and verify procedures -	$84.9K	25 - 33
• Establish System Description, Procedures, etc. -	$129.4K	25 - 33
	$2,019.6K	

CDTI Schedule and Budget

The accompaning chart summarizes the recommended schedule and budget for pursuing Phase II of the TCAS-CDTI project. Tasks shown are those summarized on the previous chart.

APPENDIX A

SIMPLIFIED ANALYSIS OF RELATIVE POSITION AND VELOCITY ESTIMATES

A brief and simple analysis is given below for the relative position and velocity estimation errors that can be expected from the TCAS sensor. The analysis is performed with respect to three active CDTI application geometries. These are the in-trail-following, dependent parallel and independent parallel approach applications as shown in Fig. A.1.
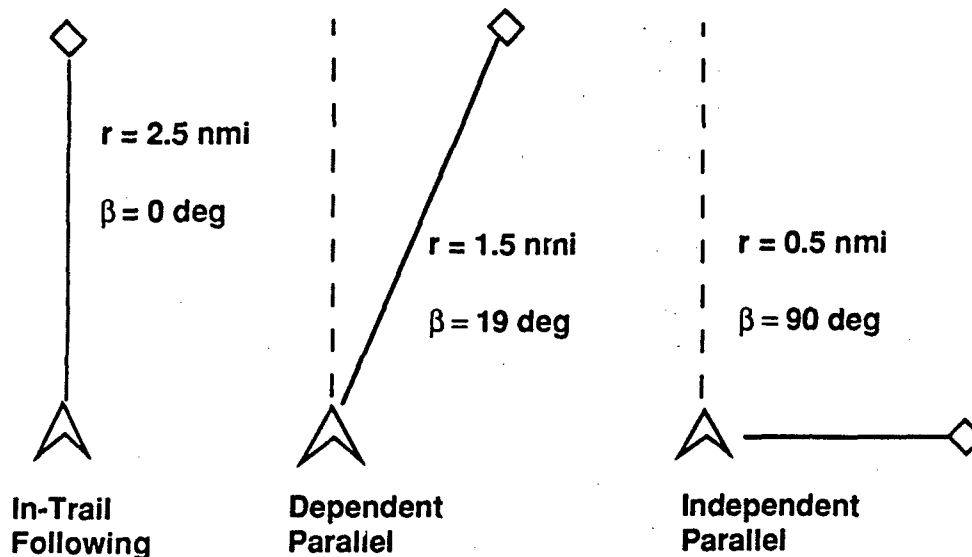
- **Examples**

Figure A.1. Example Geometry of Three CDTI Applications.

In this analysis, only the TCAS/CDTI surveillance errors in range and bearing are considered. Figure A.2 shows a schematic flow-chart of the analysis model. This indicates that errors are added to the range and bearing terms to produce the measurement values. These values are transformed to Cartesian coordinates relative to the Own aircraft heading. These X-Y coordinates are processed using an alpha-beta tracker mechanization. Table A.1 summarizes the mathematical model used in this analysis.
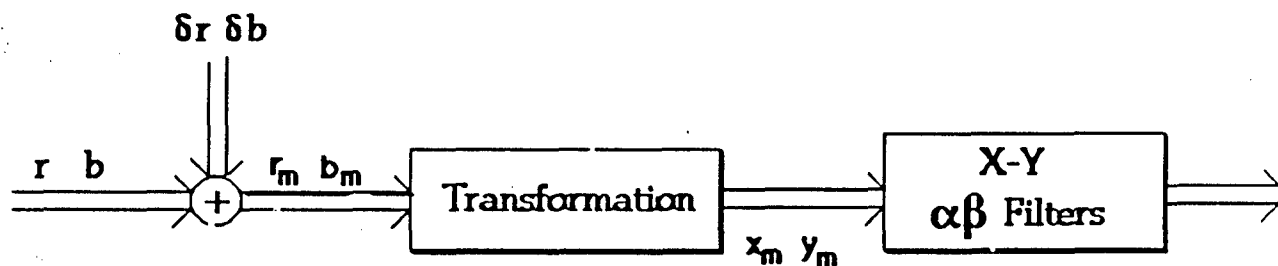
85

δr δb

r b → (+) → r_m b_m → | Transformation | → x_m y_m → | X-Y αβ Filters | →

Figure A.2. Schematic Flow Chart of Analysis Model

Table A.2 shows the expected lower bounds on the position and velocity estimation accuracy. In reality, other factors need to be considered.

As depicted in Fig. A.3, a more refined and complete analysis would include:

- TCAS/CDTI surveillance error spectrum (i.e., TCAS II, III or new specification);

- TCAS/CDTI surveillance coverage reliability model;

- Target Mode C altitude error;

- Own attitude errors;

- Relative dynamics and kinematics effects;

- Pilot reaction time effects;

- CDTI monitor logic; and

- Resulting TCAS Operating Characteristics (Missed Alarm and False Alarm Probabilities)

TABLE A.1 Mathematical Model of TCAS Surveillance and Tracking System

Range and Bearing Measurements:

$$r_m = r + \delta r; \qquad \sigma_r = 200 \text{ ft}$$
$$b_m = b + \delta b; \qquad \sigma_b = 5 \text{ deg.}$$

Transformation:

$$x_m = r_m \cos b_m = x + \delta x;$$
$$y_m = r_m \sin b_m = y + \delta y;$$

where

$$\sigma_x^2 = \cos^2 b \; \sigma_r^2 + r^2 \sin^2 b \; \sigma_b^2,$$
$$\sigma_y^2 = \sin^2 b \; \sigma_r^2 + r^2 \cos^2 b \; \sigma_b^2.$$

Alpha-Beta Filter Algorithm:

$$x_+ = x_n + \Delta x_n; \qquad \text{Prediction,}$$
$$x = x_{mn+1} - x_+; \qquad \text{Feed back error,}$$
$$x_{n+1} = x_+ + \alpha x; \qquad \text{Position update,}$$
$$x_{n+1} = x_n + \beta x/\Delta; \qquad \text{Velocity update,}$$

where

$$\Delta = 1 \text{ sec}$$
$$\alpha = 0.18, \text{ and}$$
$$\beta = 0.0091.$$

Estimation Error Covariances:

$$\sigma_x^2 = E(x - x)^2 = \{2\alpha^2 + \beta(\cap 3\alpha)\}\sigma_x^2/\text{Den}$$
$$\sigma_x^2 = E(x - x)^2 = \{2\beta^2\}\sigma_x^2/\Delta^2/\text{Den},$$
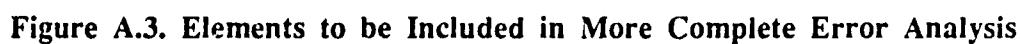
where
$$\text{Den} = \alpha(4-\beta-2\alpha).$$

Figure A.3. Elements to be Included in More Complete Error Analysis

TABLE A.2. Position and Velocity Estimation Lower Bounds for the Three CDTI Active Applications

C DTI Application	σ_x (ft) σ_y (ft)	σ_x (ft) σ_y (ft)	σ_x (ft/sec) σ_y (ft/sec)
(A) Intrail Following	200 1310	98 645	10 66
(B) Dependent Parallel	323 788	159 388	16 39
(C) Independent Parallel	260 200	128 98	13 10

REFERENCES

1. Davis, D., "TCAS CDTI Project Plan," FAA Engineering Field Office, Hampton, VA, February 22, 1990.

2. Anon., "Limited Installation Program (LIP)," Final Report jointly published by Honeywell, Inc. and Northwest Airlines, July 1989.

3. Anon., "Honeywell/Northwest Airlines Limited Installation Program (LIP)," Final Report, Pub. No. 16-3841-14-00, 1989.

4. LaFrey, Raymond R., "Parallel Runway Monitor," The Lincoln Laboratory Journal, Vol. 2, No. 3, Fall 1989.

5. Anon., "Airport Capacity Enhancement Plan 1989," DOT/FAA/CP/89-4, Transportation Systems Center, Cambridge, MA, May 1989.

6. Harmon, W. H., "TCAS: A System for Preventing Midair Collisions," The Lincoln Laboratory Journal, Vol. 2, No. 3, Fall 1989.

7. Love, W. D., McFarland, A. L., and Ludwick, J. S., "A Concept for Reducing Oceanic Separation Minima Through the Use of a TCAS-Derived CDTI," NASA CR-172258, Washington, D.C., January 1984.

8. Lebron, J. E., and Mulder, S. J., "System Safety Study of Minimum TCAS II for Instrument Weather Conditions," DOT/FAA/PM-85/12, Washington, D.C., June 1985.

9. Zarrelli, L. B., "TCAS II Logic Performance During Phase One Operational Evaluation," DOT/FAA/PM-84/20, Washington, D.C., October 1984.

10. Chappell, S.L., Billings, C.E., Scott, B.C., Tuttell, R.J., Olsen, M.C., and Cozon, T.E., "Pilots' Use of a Traffic Alert and Collision Avoidance System (TCAS II) in Simulated Air Carrier Operations," NASA TM-100094, NASA Ames Research Center, Moffett Field, CA, 1989.

11. Andrews, J. W., "Modeling of Air-to-Air Visual Acquisition," The Lincoln Laboratory Journal, Vol. 2, No. 3, Fall 1989.

12. Sorensen, J. A., and Goka, T., "Analysis of In-Trail Following Dynamics of CDTI-Equipped Aircraft," J. of Guidance, Control, and Dynamics, Vol. 6, No. 3, May-June 1983.

13. Sorensen, J. A., "System Modeling to Predict Pilot Performance During an In-trail Following Experiment," AMA Report No. 83-16, NASA Contract No. NAS1-16135, Ames Research Center, Moffett Field, CA, July 1983.

14. Goka, Tsuyoshi, "Enhanced TCAS II/CDTI Traffic Sensor Digital Simulation Model and Program Description," NASA CR 172445, Langley Research Center, Hampton, VA, October 1984.

15. Connelly, M.E., "Simulation Studies of Airborne Traffic Situation Display Applications," Final Report, MIT ESL-R-751, Cambridge, MA, May 1977.

16. Williams, D. H., "Time-Based Self-Spacing Techniques Using Cockpit Display of Traffic Information During Approach to Landing in a Terminal Area Vectoring Environment," NASA TM-84601, Langley Research Center, Hampton, VA, 1983.

17. Williams, D. H., and Wells, D. C., "Jet Transport Operations Using Cockpit Display of Traffic Information During Instrument Meteorological Conditions," NASA TP-2567, Langley Research Center, Hampton, VA, May 1986.

18. Hart, S. G., and Wempe, T. E., "Cockpit Displays of Traffic Information: Airline Pilots' Opinions about Content, Symbology, and Format," NASA TM 78601, Ames Research Center, Moffett Field, CA, August 1979.

19. Palmer, E. A., et al, "Perception of Horizontal Aircraft Separation on a Cockpit Display of Traffic Information," Human Factors, Vol. 22, No. 5, October 1980.

20. Mundra, A.D., and Buck, W. W., "The Need for Multiple VFR Approach Concepts," MP-89W00047, Mitre Corporation, McLean, VA, November 1989.

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